MATHEMATICAL SIMULATION OF A SOLAR DRYING SYSTEM

BY

JOSE ANTONIO TORRES

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TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS....ii

LIST OF TABLES....v

LIST OF FIGURES....vi

KEY TO SYMBOLS....viii

ABSTRACT....x

CHAPTERS

I INTRODUCTION....1

II REVIEW OF LITERATURE....3

Introduction....3
Performance of Collectors....7
Drying Model....13
Economic Analysis....18

III OBJECTIVES....22

IV MODEL DEVELOPMENT....23

Overall Description of the Model....23
Input Variables....26
Determination of the Incident Angle....36
Determination of Direct and Diffuse Radiation....40
Collector Analysis....44
Collector Type I....45
Emissivity factor between the cover and the absorber....51
Derivation of ρ_{12S} factor....54
Assumptions and determination of unknown optical properties....56
Film convection coefficient....58
Development of the final equation for collector type I....60
Collector Type II....66
Collector Type III....72

Drying Model....74
Economic Analysis....78

V VALIDATION AND OBSERVATIONS....80

Drying Model....80
Verification of the Collector Performance....82
Collector Type I....82
Collector Type II....84
Collector Type III....86
Final Observations....89

VI CONCLUSIONS....93

APPENDICES

A DEVELOPMENT OF EQUATIONS FOR COLLECTOR TYPE II....95

B DEVELOPMENT OF EQUATIONS FOR COLLECTOR TYPE III....107

C EQUATIONS TO CALCULATE TRANSMISSION THROUGH THE COVER....114

D NEWTON-RAPHSON METHOD FOR A SYSTEM OF NONLINEAR EQUATIONS....117

E SCREENS FOR SELECTION OF COLLECTOR MATERIALS....121

F SAMPLE COMPUTER PRINTOUT....124

G DESCRIPTION OF SUBROUTINES AND FUNCTIONS....129

H LIST OF VARIABLES....142

I PROGRAM SOURCE CODE....157

REFERENCES....226

BIOGRAPHICAL SKETCH....232

LIST OF TABLES

Table		Page
1	Coefficients for the Piecewise Linear Function $K_B = A_i K_T + B_i$	42
2	Known and Unknown Optical Properties of Collectors	57
3	Comparison of Energy Required to Dry the Corn and the Sensible Energy Given Up By the Air	81
4	Simulated Resuts with SOLDRY for Collector Type I, Using Data from October 1985	84
5	Simulated Results with SOLDRY for Collector Type II, Using Data from Gainesville, FL, November 1985	87
6	Simulated Results with SOLDRY for Collector Type III, Using Data from Gainesville, FL, June 1985	87
7	Comparison of Simulation Results from Parker and SOLDRY for Collectors Type I, II and III	88
8	Simulation Results Using SOLDRY for Comparing the Three Types of Collectors Using Two Different Cover Materials and At Four Different Airflow Rates	90

LIST OF FIGURES

Figure		Page
1	Inputs and Outputs of the Model	24
2	Flow Diagram of Main Program	27
3	Calculation of Areas and Dimensions for Right Angle Collector	30
4	Calculation of Areas and Dimensions for Isosceles Triangle Collector	31
5	Calculation of Areas and Dimensions for Rectangle Collector	32
6	Calculation of Areas and Dimensions for Semicircle Collector	33
7	Solar Angles	37
8	Percent of Direct Radiation K_B as a Function of the Percent of Total Horizontal Radiation K_T (Kreider and Kreith, 1981, p. 2-67)	42
9	Flowchart of Subroutine PERFORMANCE	46
10	Schematic Diagram of the Heat Balances on Collector Type I	47
11	Ray Trace of Energy Emitted by the Absorber	52
12	Ray Trace of Energy Emitted by the Cover to the Sky and to the Absorber	55
13	Energy Balance on Fluid, Collector Type I	62
14	Schematic Diagram of Heat Balances on Collector Type II	67
15	Schematic Diagram of Heat Balances on Collector Type III	73

16 Collector Efficiencies as a Function of Airflow Rate Per Unit of Absorber Area.....83

17 Comparison of Field Data with SOLDRY Model Simulation Results, Collector Type II.....85

18 Heat Balances on Air Flowing Through Channels 1 and 2 on Collector Type II.....96

19 Heat Balance on Air Channel on Collector Type III.....109

KEY TO SYMBOLS

The definition of symbols in this list is only valid for symbols written within the section "Collector Analysis" in chapter IV and for appendices A and B. Subscripts (1), (2) and (3), unless specified otherwise, refer to the respective part of the collector as defined on figures 10, 14 and 15.

A_4	Ratio of cover area over absorber area.
A_5	Ratio of case area over absorber area.
A_6	Area of segment in which collector has been divided to simulate its performance.
C_p	Specific heat of the air.
D_e	Equivalent diameter of the cross sectional area of collector.
G	Mass flow rate of the air going through the collector.
h	Film convection coefficient.
h_B	Convection coefficient at the bottom of the case.
h_w	Convection coefficient due the wind.
k	Thermal conductance of the air.
Nu	Nusselt number.
Nu_{local}	Local Nusselt number.
Nu_∞	Nusselt number for fully developed flow.
Pr	Prandtl number.
R_B	Thermal resistance of the case.
Re	Reynolds number.

T	Absolute temperature.
T_a	Absolute temperature of the air (dry bulb).
T_f	Absolute temperature of the air going through the collector.
T_{sky}	Absolute temperature of the sky.
V	Air velocity through the collector.
α	Absorptivity.
ε	Emissivity.
ε_{12L}	Emissivity factor between cover and absorber (collectors type I and II).
ε_{23L}	Emissivity factor between absorber and case (collectors type II and III).
ρ	Reflectivity.
ρ_{12S}	Reflectivity factor bewtween cover and absorber (Collectors type I and II).
σ	Stephan Boltzman Constant.
τ	Transmissivity.

Subscripts

L	Long wavelength radiation.
S	Short wavelength radiation.

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JOSE ANTONIO TORRES

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A mathematical model for a solar drying system was developed and is presented as an interactive computer program. The collector performance and drying routines are based on existing algorithms; however, the equations for performance were fully revised and written so any material can be used for the collector. The model is completely documented including the assumptions made.

The model provides several options for collector type and cross sectional shape. The user can also choose between different materials for the collector cover, absorber and insulation. The airflow rate, time of the year during which the collector is going to be used and the amount of grain to be dried are also entered by the user. The model reads weather conditions, estimates the amount of direct and diffuse radiation falling on the collector and simulates the collector performance. A drying routine based on the logarithmic drying model estimates the average moisture content of the product and determines whether or not the grain has reached the desired moisture content.

Once the final moisture content is reached, an economic analysis is performed and the outputs written.

This model, although intended for farmers and county agents in determining the feasibility of solar drying systems, would also be useful for researchers to study the importance of certain parameters such as effect of orientation of the solar collector, how the optical properties of the collector materials affect the collector efficiency and the overall economics, etc.

CHAPTER I
INTRODUCTION

Agriculture is an industry strongly dependent on energy and is vulnerable to fuel shortages and fuel price increases. It has been proposed that farmers look for new sources of energy which would make them less dependent on fossil fuels. Crop drying accounts for 3.5% of the total energy consumed in agriculture. In 1980 more than 70,000 billions kJ were used for drying; 13% of the energy used was fuel oil, 86% liquid petroleum (L.P.) gas and 1% natural gas (Heid et al., 1982).

Grain drying in farms is usually done with air at temperatures less than 54 C (130 F). Sometimes the grain is harvested at high moisture content and dried at temperatures higher than 54 C until the grain reaches a moisture content of approximately 22% wet basis. Then low airflow rates and low temperatures are used to dry the grain to the desired moisture content.

Air-type solar collectors, under normal conditions, can heat ambient air 5 to 15 C (10 to 30 F) allowing the farmer to save on fossil fuels. However, solar energy is not a concentrated source of energy and requires large collection areas. Also the availability depends on weather conditions, requiring a fossil fuel back-up system and/or increased management time.

Air-type solar collectors with an efficiency of 40 percent could get about 9000 KJ per square meter per day (8 hours). The most common fuel used to heat air for crop drying is L.P. gas which has a heat content of 28,000 KJ/P (about 100,000 Btu/gal). The price for L.P. gas is about one dollar per gallon.

Based on these figures a solar collector will save the farmer about eleven cents per square meter per day. That means if the collector cost is 11 dollars per square meter then it requires about 100 days to pay for the collector. The payback period will be longer than a year since the drying period is usually less than 100 days.

From the previous analysis one can conclude that collector materials should be inexpensive and that the drying season should be extended as long as possible. Many studies have been published on solar collectors and solar drying systems (Parker, 1980a, b, c; Fitzgibbons and Kline, 1978; Pierce and Thompson, 1976). However, no model was found which analyzed the performance of collector, took into account the constrains of the drying process and performed an economic analysis on the system. This type of model would be useful for a farmer, for a county agent and for solar material manufacturers. Also, it would be a useful tool for researchers, engineers and nonengineers.

CHAPTER II
REVIEW OF LITERATURE

Introduction

Drying of food products is a common practice in agriculture. Until very recently, during the 1950s, and still now on a worldwide basis, crops were left to dry in the field. The advances in mechanization and higher competition on the market forced American farmers to use artificial drying. Some advantages of drying are that it gives the farmer more control over the management of the crop. Early harvesting will give the farmer more time to grow another crop and probably to sell it at a better price. Dried products have a longer storage life, thus allowing long term storage and giving the farmer time to wait for the best price, Henderson and Perry (1981). Maximum yield for corn occurs when harvested at 26% moisture content, Johnson and Lamp (1966); however, the decision of when to harvest should be based on when it is more profitable rather than yield production.

Chau (1980) classified drying systems according to the different air temperatures used: air drying when the air is only heated by the fan 1.0 - 1.5 C (2 - 3 F), low temperature dryers when air is heated 15 - 30 C (30 - 55 F), medium temperature dryers when air is heated 60 - 70 C (110 - 125 F), and finally, high temperature dryers when air is heated above 70 C (125 F). Natural and low temperature drying can be

done in places where low temperature and low relative humidity exist. Sometimes a combination of high and low temperature drying is used. This practice allows the farmer to save energy and have a better quality product.

Initial interest in solar drying in the U.S. was primarily in the Midwest where it was used to replace or supplement natural or low temperature drying. Solar energy was seen as a way to reduce drying time and save money on electricity to drive the fan and on fuel for heating the air. Studies by Buelow (1962) proved solar energy to be technically feasible; however, the price of fossil fuels was too low and hence solar energy could not compete favorably. In 1973, after the oil crisis, solar energy became popular again. The U.S. government started funding research on solar drying operations and their economic feasibility (Foster et al., 1980). During the earlier stages of the program some research on in-storage grain drying systems was developed. Two main constraints were found: solar drying systems were not used enough time within a year to justify the investment and these systems could not dry large amounts of grain due to their inherent intermittency and low temperature. To overcome these two problems, mixed systems where solar collectors were used for more than one activity, i.e., dry grain and heat a hog house, and using solar collectors as preheaters were proposed.

In 1978, Thompson and Pierce ran simulations of drying corn at different moisture contents and at different places within the U.S. They found that minimum airflow rate requirements per bushel doubles when corn is harvested at a moisture content two points higher.

Minimum air flow rate increases faster when the temperature of the grain is higher. They concluded that solar grain drying could be feasible when the initial moisture content of corn is 22% or less. These results are valid for the south and central part of the U.S. Heid and Aldis (1981) came to the same conclusion for the Central Great Plains.

Saul and Lind (1958) studied the relationship between grain respiration and biological activity on corn. They measured the carbon dioxide production on the grain and found that mold grows much faster when the equilibrium relative humidity is 99% or higher. They also determine a correlation between dry weight loss from grain with specific air flux. Specific air flux is the volumetric flow rate of air per volume of grain.

Steele et al. (1969) determined the relationship between percentage of grain spoiled versus time. They took into account temperature of the grain, mechanical damage and initial moisture content. They draw several curves of storage temperature versus permissible storage time for different moisture contents. Permissible storage time was defined as the maximum time a grain can be stored before 0.5% of its original dry matter content is lost due to respiration and mold growth. The findings of these two investigations are very important when developing mathematical models for drying and storage of grain.

Grain drying in the southeast is different from the north and central part of the U.S. where more than 8 weeks are typically used to dry the grain. In the southeast grain is harvested early when

temperatures and relative humidity of ambient air are high favoring mold growth. Much shorter time can be used for drying, requiring higher airflow rates and higher air temperatures for safe drying (Chau and Baird, 1980). A temperature rise of 8 to 10 C (15 to 20 F) with airflow rates above 0.47 m^3/h-Kg (6 CFM/Bu) are common in Florida. Even though drying has to be done faster in the southeast it is possible to grow more crops per year giving the opportunity to use the solar system longer.

Solar drying is not limited to grain drying. Many countries specially those within the tropics have used solar drying to dry crops such as cocoa and coffee. Usually these products are laid out on terraces or on open hard soils during the day and collected at sunset to protect them from dew. If there were an inexpensive way to hasten the drying, it would help these countries to lower the percentage losses of food products. There have been some dryer designs with good possibilities of success. One of these is a thin wall filled with cassava, or the product to be dried, where the product is exposed to the sun and to the wind so the drying is more effective. Sun rays heat the product while the wind forces the air to pass through the wall. Another type is a vegetable/fruit dryer where the product is put on screens one on top of the other and spaced so sunrays fall on each layer. Also on the ground there is a solar collector that heats the air before it is conducted to the screens. This system looks like a tower with several floors where fruits or vegetables are dried and is intended for small scale drying.

Solar drying appears to be very promising in tropical countries. The actual technology for solar drying systems and the economic feasibility is strongly dependent on the amount of time that the system is used during the year. These two requirements could be easily met in these countries; however, some other problems may appear such as lack of electricity in the farm to drive fans and difficulty to bring fuels to the farm. In any case the technology used in agriculture depends on the experience and the knowledge of the farmers. A simulation model would be a powerful learning tool not just to introduce a new technique but also to communicate between researchers and farmers.

Performance of Collectors

Solar systems are usually classified into two groups, passive and active. When there is no mechanical part on the system, it is called passive. An example of a passive type is the vertical wall filled with cassava mentioned in the previous section. Here two forms of solar energy are used, insolation and wind. Other systems need another source of energy such as electricity or gasoline to drive fans. These systems are called active. The solar grain drying systems studied in this report are all active. A fan forces air through solar collectors where it is heated and then pushed through the grain.

Solar air-type collectors, also called air heaters, can be classified by the position of the solar energy absorber with respect to the working fluid, Parker (1980a). When the air flows above the

absorber, the collector is said to be type I. Type II collectors are those in which the absorber is between the case and the cover and air can flow on both sides of the absorber. This type of collector is very appealing since the temperature of the absorber is lower, diminishing collector heat losses. Collector type III has the absorber directly above the airflow channel. The bare plate collector is an example of this collector type. Parker (1980c) compared these three types with two and three covers and for different inlet air temperatures. Type II collectors are usually more efficient; however, if high temperatures are desired then type III collectors with at least one cover could be more efficient. It is important to notice that for grain drying inlet air will always be at ambient temperature and no more than two covers would be found. The selection of the collector type should be based on which system is more economical for the farmer. If the drying facility is close to a barn it is possible that retrofitting would be the best alternative. If no buildings are available a large plastic solar collector may be better.

Although the analysis of solar air heaters is very similar to water-type heaters, two important distinctions have to be made. Air has very low heat capacity (about one quarter that of the water) and the ratio of fluid mass over absorber area is much lower for solar air heaters than for water heaters (Parker, 1980b). To compensate for these two disadvantages one might want to use a high airflow rate; however, higher airflow rates implies higher pressure drops and hence higher energy input requirements. Buelow (1962) recommended from 0.05 to 0.08 $m^3/s\text{-}m^2$ of collector area (10 to 15 CFM per square foot of

collector area). He also suggested that maximum pressure drop throughout the collector should be less than 24 Pa (0.1 in. water). Buelow ran experiments on collectors with rectangular cross section and determined that for 0.05 $m^3/s\text{-}m^2$ a minimum distance between absorber and cover should be 10 cm (4 in.) for a 3 m long collector (10 ft). He noticed also that the pressure drop at the entrance and at the outlet are very important. In some collectors there are purlins and other objects that increase the air turbulence inside the collectors and contribute to airflow resistance. However, these losses are small compared to entrance an exit losses and hence are neglected.

The analysis of solar air heaters is very similar to tube-type solar collectors and some of the equations used are the same for either type of collector. The main objectives of the analysis are to determine thermal efficiency, outlet air temperature and useful heat. Performance of collectors can be evaluated instantaneously or daily.

The most widely used equation to calculate the useful heat recovered by a collector is the Hottel-Whillier equation (Hottel and Whillier, 1955). This equation states that the useful energy is equal to the net radiation reaching the collector absorber minus the losses of the collector. Normally the collector losses are taken at the average absorber temperature; however, since it is more important to know the average fluid temperature than the plate temperature, then a factor F' was created. This factor is called the collector efficiency factor and is defined by Hottel and Whillier (1955) as the rate of the actual useful heat collected divided by the useful heat collected if

the average absorber temperature were at the actual average fluid temperature.

$$q_u = F' [(\tau\alpha)_e I - U_L (T_f - T_a)] \quad (1)$$

where

q_u = useful heat per unit area of collector.

F' = collector efficiency factor.

U_L = overall loss coefficient.

$(\tau\alpha)_e$ = effective transmittance-absorptance product.

I = incoming solar radiation incident to collector.

T_a, T_f = average ambient and fluid temperatures.

This collector efficiency factor, F', gives an indication of how efficient the air is removing heat from the absorber. Duffie and Beckman (1974, pp 142,143) noticed that on some shapes of collectors F' can be interpreted as the ratio of the thermal resistance from the plate to the ambient divided by the resistance from the fluid to the ambient. The overall loss coefficient, U_L, is the inverse of the lump sum of thermal resistances from the absorber to the ambient. The effective transmittance-absorptance factor accounts for more than the net radiation absorbed by the collector. This factor takes into account energy reflected by the absorber and cover and then absorbed by the absorber. It also considers the energy absorbed by the cover. Generally, the cover is assumed to have an absorptivity equal to zero; however, the energy absorbed by the cover(s) raises the

temperature of the cover and radiation losses from the absorber to the cover(s) become smaller.

The collector parameters F' and U_L are functions of film convection and radiation coefficients; however, these do not show an explicit relation with air flow rate. Also, in practice, it is very difficult to measure the average fluid temperature. Bliss (1959) defined another factor called the heat removal factor, F_r. The heat removal factor is defined as the rate of actual useful heat over the rate of useful heat collected if the plate were at the inlet fluid temperature. The Hottel-Whillier equation is modified and becomes the so called Hottel-Whillier-Bliss equation:

$$q_u = F_R [(\tau\alpha)_e I - U_L (T_i - T_a)] \qquad (2)$$

where T_i = inlet fluid temperature. Duffie and Beckman provided an equation for F_R:

$$F_R = \frac{GC_p}{U_L} [1 - e^{(-F'U_L / G C_p)}] \qquad (3)$$

where

G = air mass rate per unit of collector area.

C_p = specific heat of the air.

This equation shows explicitly the effect of the airflow rate on the collector performance.

Equations to calculate F'and U_L are found in the literature (Parker 1980b, p. 28), Duffie and Beckman (1974, p. 164, 165). These

equations were made assuming average temperatures for cover(s), fluid and absorber. Also radiation from the absorber to the sky was neglected. This last assumption is due to the fact that originally collector covers were glass which is transparent for solar radiation and opaque for long wavelength radiation such as that emitted by the absorbers. Solar air heaters very frequently use plastics for covers. Since plastics are transparent for both short and long wavelengths radiation losses from absorber should be considered.

Practically all collector performance analyses used the Hottel-Whillier-Bliss equation. This equation, however, is only valid at a certain condition where the temperatures of the air, cover(s) and absorber are the averages of the collector. These temperatures are used to calculate convection and radiation film coefficients. Parker (1981b) pointed out that these temperatures do not need to be too exact to give a good estimation of collector performance because F', and U_L are not very sensitive functions of the temperatures.

Fitzgibbons and Kline (1978) present a method to calculate performance on a suspended plate collector (type II collector). They use two equations of the Hottel-whillier type and added a third factor for heat exchange between both sides of the absorber. This method is iterative and requires a computer for calculations. Parker (1980b) presents graphs obtained by calculating performance for different inlet air temperatures and for different mass flow rates. These graphs were used by Petersen and Morrison (1984) to explain design parameters to solar collector constructors.

Chau (1981) used direct heat balance equations to analyze performance of collectors. Although the system of equations is non-linear, the number of unknowns is less than in some other approaches. This method will be explained later in development of the model.

Drying Model

The drying process is divided in two periods called the constant rate period and the falling-rate period. During the constant rate period the water removal depends only on the amount of energy available from the air and not on the characteristic properties of the product. During this period the water removal would be equivalent to that from a lake or free water surface. The falling rate period starts when internal forces of the product hold the remaining moisture and more energy is required to remove the water. Grain and cereals are harvested at a moisture content such that artificial drying takes place only within the falling rate.

Drying simulations have almost always been done based on empirical equations (Flood et al. 1972, Bloome and Shove 1971, and Thompson 1972). An analytical solution for drying was proposed by Luikov (1966). Six mechanisms were recognized to take part in the drying process:

1) "Liquid movement due to surfaces forces.
2) Liquid movement due to moisture concentration differences.
3) Liquid movement due to diffusion of moisture on the pore surfaces.

4) Vapor movement due to moisture concentration differences.

5) Vapor movement due to temperature differences.

6) Water movement due to total pressure differences." (Brooker et al., 1981, pp. 187, 188).

The complexity of the solution and the lack of knowledge of some of the terms makes this approach difficult to follow. Usually it is assumed that the only mechanisms involved in the drying process are vapor and liquid diffusion. Kusumowardhoyo (1981) showed experimentally that this assumption is correct and that, even though water might migrate through liquid diffusion, the main mechanism is vapor diffusion. Luikov's solution, after been simplified, has the following form:

$$\frac{M_t - M_e}{M_o - M_e} = A\, e^{-Kt} \qquad (4)$$

where

M_t = moisture content dry basis, decimal.

M_e = equilibrium moisture content dry basis, decimal.

M_o = initial moisture content dry basis, decimal.

A = constant, depends on the shape of the product, dimensionless.

K = Drying constant, 1/s or 1/h.

t = time, s or h.

The drying constant, K, is a function of the mass diffusivity shape and configuration of the product. This constant is found experimentally therefore its application is valid for a specific

product and at certain temperature ranges only (Brooker et al. 1981). Pabis and Henderson (1961) determined constants in equation (4) for corn assuming the shape of the corn as a brick:

$$K_{corn} = 5.4 \times 10^{-1} e^{5023/T_{abs}} \quad (5)$$

where $A = 0.8106\ (8/\pi^2)$. For wheat and barley O'Callaghan et al. (1971) presents the following constants:

$$K_{wheat} = 2000\ e^{-9179/T_{abs}} \quad (6)$$

$$K_{barley} = 139.3\ e^{-7976/T_{abs}} \quad (7)$$

where

$A = 1.$

T_{abs} = absolute temperature of the product.

Hukill (1947) developed a model usually called the Logarithmic model for bulk drying. He derived an equation which stated that the latent heat required to remove the moisture is equal to the sensible heat lost by the air:

$$G\ C_p \frac{\partial T}{\partial y} = \rho_{grain}\ L \frac{\partial M}{\partial t} \quad (8)$$

where

C_p = specific heat of the air.

G = air mass flow rate per unit mass of grain.

L = latent heat of vaporization of water, from the grain.

ρ_{grain} = density of dry matter in grain.

t = time.

y = depth.

Hukill solved the equation by inspection; however, in equation (8) the temperature gradient and the moisture rate are unknowns and since there is only one equation then there must be a second equation to solve the system analytically. Baughman et al. (1970) proposed a second equation which relates the temperature and moisture gradient:

$$G\, C_p \frac{\partial T}{\partial y} = - Q\, L \frac{\partial M}{\partial y} \tag{9}$$

where Q = rate of advance of the drying zone.

Using equations (8) and (9) the following expression can be found:

$$\rho_{grain} \frac{\partial M}{\partial t} = -Q \frac{\partial M}{\partial y} \tag{10}$$

Writing this equation in dimensionless form

$$\frac{\partial C}{\partial \theta} = \frac{-1}{1 - C(0,\theta)} \frac{\partial C}{\partial D} \tag{11}$$

where

$$C(D,\theta) = \frac{M(D,\theta) - M_e}{M_0 - M_e} \tag{12}$$

$$\theta = K\,t \tag{13}$$

and

$$D = \frac{L\,K\,(M_0 - M_e)}{G\,C_p\,(T_0 - T_e)}\,Y \tag{14}$$

The solution of equation (11) with the following initial and boundary conditions is equation (16)

$$C(D,0) = 1 \tag{15-A}$$

$$C(0,\theta) = e^{-\theta} \tag{15-B}$$

$$C = \frac{e^{D}}{e^{D} + e^{\theta} - 1} \tag{16}$$

The factors θ and D are called the time and depth factor respectively. The constant K is different from the one previously defined and has the form

$$K = P_s^{\,n}\,V^{m} \tag{17}$$

where

K = drying constant.

P_s = saturation vapor pressure.

V = air velocity through the grain.

Y = depth of product.

Earlier, it was stated that during the falling drying rate the internal forces of the product became more important than the conditions around the product. The solution for the drying equations (15) and (16) present two variables, the time factor θ and the depth factor D. The determination of these two factors does not show clearly where these internal forces are taken into account. Haynes (1961) determine the amount of energy required to evaporate the water from the grain at different moisture contents and at different temperatures. This heat of vaporization is higher than the heat of vaporization of free water to compensate for the internal forces of the grain and should be used when using the Logarithmic model.

The logarithmic model has been widely used by many researchers and for several products, and the simulations give reasonably accurate results, (Barre et al., 1971; Baughman et al., 1970; Sabbah et al., 1979). This model has been used for uniform initial conditions and fixed entrance air conditions. Sabbah et al. (1971) used it to simulate solar drying by giving hourly input conditions and by averaging data every specified amount of time.

Economic Analysis

Pierce and Thompson (1976), using a drying model, studied the impact of solar drying in the North Central Plains first, and then in the southern states where warmer weather prevails at the time of drying corn. Solar heat supplement (2-4 C) was found to have no

significant influence on the final quality of the product nor on the drying time, thus indicating that the addition of solar heat would not be economically feasible. These results were not the same for humid conditions such as in Indiana, Missouri or North Carolina. In these places, solar energy has been shown to have some potential.

Chau (1980) did an energy survey on the different drying systems used in the U.S. Although he pointed out that solar energy was not economically feasible yet, results showed that the gap is not too wide so it is possible that solar energy would be feasible in the near future when more research on solar collectors brings costs down or prices of fossil fuels go up. Partial high temperature drying followed by low temperature was mentioned as the most efficient system energywise. Corn is subject to high temperature, usually cross-flow drying, at the beginning when the moisture content of the corn is high. When the product reaches about 20 percent moisture content, the drying is finished at low temperature. During this period, solar energy could be used as an energy source.

Heid (1978) studied the economic feasibility of eight solar drying systems located in the Midwest. Although some of the systems were not set up for optimum performance, the analysis showed what items have greater impact on the economics of solar drying systems and among these items, he identify which are the ones that show the most potential for lowering costs. Costs and life expectancy of materials and electric hook ups were the most important fixed costs and maintenance of collector was the most important variable cost.

Among the eight different types of collectors three were commercial. Two commercial collectors were determined to be the most economical even though their fixed cost were higher than homemade collectors. Longer life expectancy and less maintenance caused these collectors to be more economical. Results of the study by Heid proved that solar drying systems can be economically feasible.

Heid and Aldis (1981) studied the effect of solar energy supplied to a natural air drying system in Dodge City, Kansas. Twenty years of weather data were used to simulate drying with a model developed by Van Ee and Kline (1979). Heid and Aldis compared several drying management options. Harvesting when grain was at lower moisture content was not economical because losses of the product were higher than the extra expense of drying. Drying with natural air was studied even when grain quality deteriorated and lowered the grade. Finally, drying using supplemental solar heat was tested. It was found that natural drying, no matter if grain quality deteriorates, is more economical than using solar energy. For these analyses, prices of 1979 and 1980 were used.

Keener et al. (1981) studied the optimum drying systems for North Central Ohio from the point of view of energy consumption. Energy efficiency was defined as the energy required to dry a certain amount of corn per total energy used. This total energy used accounted for the energy used for transforming raw energy into useful energy. LP gas, coal-gas, electricity, solar energy and corncobs were the energy sources studied. Other parameters used for the optimization were depth, fan size and air temperature. It was found that the most

efficient systems worked either at the highest possible temperatures or at low temperatures. Optimum depths were between 1 and 3 m (3.4 to 11 feet) and for ambient or near ambient between 1.2 and 1.8 m (3 to 6 feet). Corn cobs were the most efficient energy source followed by solar energy.

CHAPTER III
OBJECTIVES

To develop an engineering/economic model that simulates a solar drying operation for corn. This model should be able to simulate performance of the three main types of solar air heaters used in agriculture.

The model must be "user friendly" giving a variety of options that can be used by farmers and extension agents.

The model should simulate performance of collectors at any latitude and with any collector orientation and inclination.

All algorithms, equations, and assumptions must be clearly stated and documented so that engineers and scientists can modify the model when better information becomes available.

CHAPTER IV
MODEL DEVELOPMENT

Overall Description of the Model

Figure 1 shows schematically the functioning of the model. The left hand side shows all the inputs while the outputs are shown on the right hand. The intermediate variables, calculated within the program, are required to obtain the desired outputs. The definition of all the variables and constants in the model are shown in appendix H.

Constants are defined here as those parameters that do not change from one simulation to another. Three types of constants are used. The first type called "natural" constants are values that can never be changed, e.g. conversion factors. The "programmed" constants are those parameters which are used to determine how accurate the approximations can be, for example the number of segments in the collector. Finally, the "assumed" constants are those parameters that vary with some variables included in the model but the variation is very small for the the program so, in order to simplify the model, these parameters are assumed constants.

The model has six main parts. The main program includes the inputs and most of the constants used in the program and initiates many of the variables such as the time counters the initial moisture contents of each one of the corn layers, etc. The second part

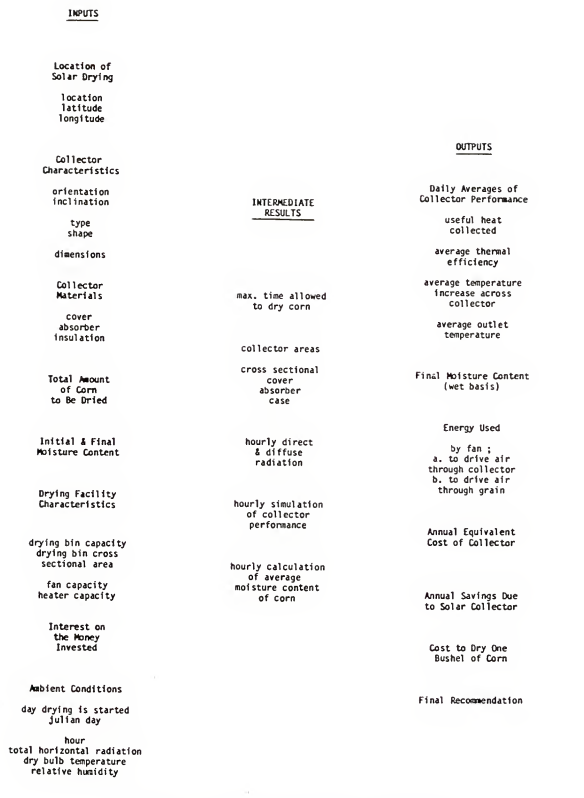


Figure 1. Inputs and Outputs of the Model.

determines the incident angle between the sun and the collector surface and estimates the direct and diffuse radiation falling on the collector cover. The third part is the simulation of the collector performance. This simulation is directed by a routine called PERFORMANCE which calculates the initial variables common to all the collector types and then calls other routines to determine the value of the functions pertaining to each collector type. This routine also checks the results to see if they are accurate enough and if not it recalculates the values until satisfactory results are found.

The routine called DRYING determines the average moisture content of the corn and performs the drying simulations every hour. At night a heater is used to heat the air going through the grain. When the average moisture content of the corn is less than the desired moisture content, then the next batch is loaded and dried to the desired final moisture content.

Once all the batches are dried a routine called ECANALYSIS determines the cost of drying one bushel of corn from the initial moisture content to the desired final moisture content. To do so the initial costs of the collector materials, the fan and the heater are spread over their useful life and that cost added to the annual costs giving the total operating cost of the system per year. This total cost is divided by the amount of bushels dried during the year to obtain the desired output.

The value of the annual fuel savings is compared with the annual operating cost to give the net savings provided by the solar collector.

The last part of the model is composed of two routines SUBOUT1 and SUBOUT2 and several write statements on the main program which are responsible for the output file called USERFILE. Figure 2 shows the flow of the main program.

Input Variables

Since the model is intended for farmers and other nonengineers the required inputs are stated as simple as possible making the program "user friendly". The location of the drying system is defined by the nearest town, latitude and longitude. The collector characteristics are input next.

The important characteristics for collector performance are collector orientation (which by convention is measured from the south and counterclockwise), the inclination of the collector surface with respect to the horizontal plane, the collector type and shape and the collector dimensions. Three types of collectors are included in this model: collector type I in which air flows above the absorber, collector type II where air flows on both sides of the absorber, and type III where air flows underneath the absorber. A bare plate collector is a special case of collector type III. The model is restricted to simulate the collector types I and II with one cover only, and bare plate collectors for type III.

Four different cross sectional shapes are presented in the model: a triangular shape with a square angle, an isosceles triangular shape, a rectangular shape and a semicircular shape. The next input set is dimensions. For all the different cross sectional shapes length,

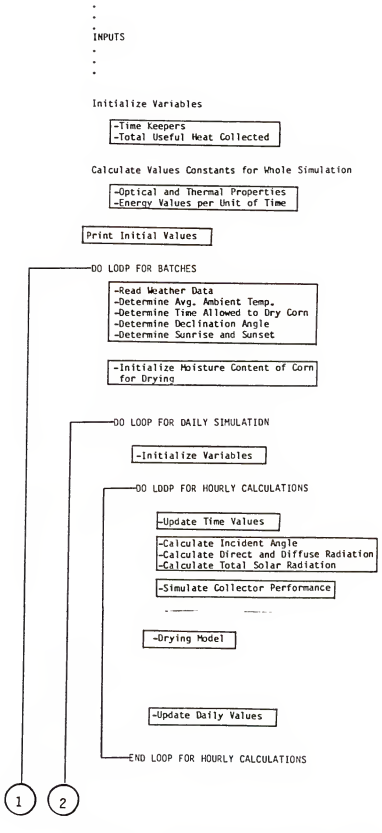


Figure 2. Flow Diagram of Main Program.

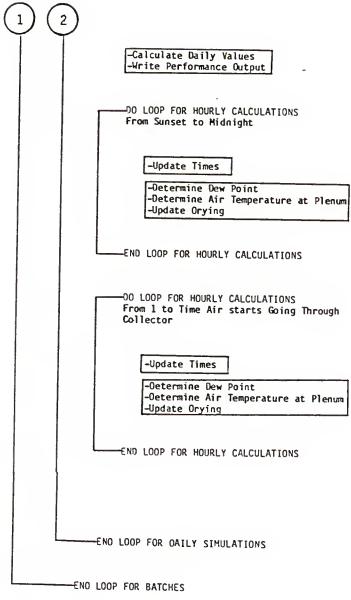
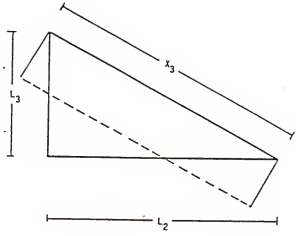


Figure 2--continued.

width and height are input. For the suspended plate collectors (collectors type II) the height between the bottom and the absorber is also entered. The cross sectional areas are calculated with the equations shown in Figures 3 through 6. For type II collector, the cross sectional area of each channel is calculated. Only two shapes can be used with collector type II, rectangular and semicircular.

Collector materials are those used as covers, absorbers and insulators. The important characteristics of these materials are optical and thermal properties, and costs. The optical properties entered for the cover are average long wavelength transmissivity, average short wavelength transmissivity and short wavelength transmissivity as a function of the solar incident angle. Godbeys et al. (1977), determined experimental values for different cover materials at different incident angles. A nonlinear regression curve, using seven points, was determined for each one of the materials used and the equation included in a function called TRANS. Appendix C presents the data found by Godbeys et al. (1977) and the equations used in the model.

The optical properties input for the absorber are short wavelength absorptivity and average long wavelength emissivity. The thermal resistance as well as the thickness of the insulation materials are input also. Since not all of the optical properties are input, some assumptions have to be made. These will be discussed when explaining the performance of collector type I. The costs of materials are broken into initial costs, installation costs and annual maintenance costs. Installation costs not only account for the labor



$$X_3 = (L_2^2 + L_3^2)^{0.5}$$

$$A_{side} = 0.5 * L_3 * L_1$$

$$A_{end} = 0.5 * L_2 * L_3$$

$$A_{edge} = 2 * (A_{side} + A_{end})$$

$$PERIMETER = L_2 + L_3 + X_3$$

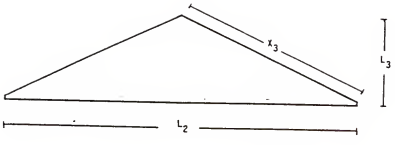
$$A_{cross\ section} = 0.5 * L_2 * L_3$$

$$A_{absorber} = L_1 * X_3$$

$$A_{cover} = L_1 * X_3$$

$$A_{bottom} = A_{absorber} + A_{edge}$$

Figure 3. Calculation of Areas and Dimensions for Right Angle Collector.



$$X_3 = \left(\left(\frac{L_2}{2}\right)^2 + L_3^2\right)^{0.5}$$

EDGE = 0.33
Assume the edge is 10 cm (0.33 ft) height.

$A_{side} = L_1 * EDGE$

$A_{end} = 0.5 * L_2 * L_3$

$PERIMETER = 2 * X_3 + L_2$

$A_{cross\ section} = 0.5 * L_2 * L_3$

$A_{cover} = 2 * L_1 * X_3$

Figure 4. Calculation of Areas and Dimensions for Isosceles Triangle Collector.

$A_{side} = L_1 * L_3$

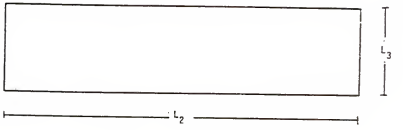
$A_{end} = L_2 * L_3$

$A_{absorber} = L_1 * L_2$

$A_{cover} = L_1 * L_2$

$A_{bottom} = 2 * (A_{side} + A_{end})$

For collectors type I and III



PERIMETER = $2 * (L_2 + L_3)$

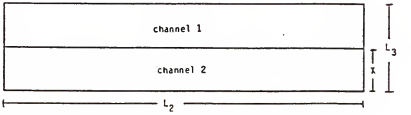
$A_{cross\ section} = L_2 * L_3$

For collectors type II

Channel 1

PERIMETER = $2 * ((L_3 - X) + L_2)$

$A_{cross\ section} = L_2 * (L_3 - X)$



Channel 2

PERIMETER = $2 * (L2 + X)$

$A_{cross\ section} = L_2 * X$

Figure 5. Calculation of Areas and Dimensions for Rectangle Collector.

$A_{edge} = 28.3$ (assumed)

$A_{end} = 2 * A_{edge}$

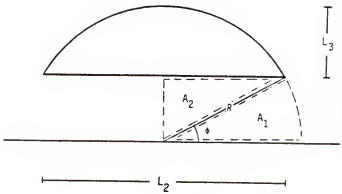
$A_{bottom} = A_{absorber} + A_{end}$

$$R = \frac{L_2^2}{8 * L_3} + \frac{L_3}{2}$$

$$\phi = \text{asin}\left(\frac{R - L_3}{R}\right)$$

$PERIMETER = L_2 + R * (\pi - 2 * \phi)$

$A_{cover} = L_1 * (PERIMETER - L_2)$



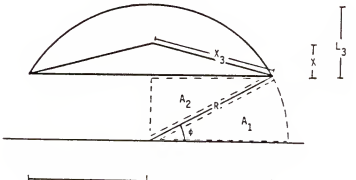
For Collectors type I

$$A_1 = R^2 * \frac{\phi}{2}$$

$$A_2 = 0.5 * \frac{L_2}{2} * (R - L_3)$$

$A_{12} = 2 * (A_1 + A_2)$

$$A_{cross\ section} = \pi * \frac{R^2}{2} - A_{12}$$



For collector type II

$$X_3 = \left(\left(\frac{L_2}{2}\right)^2 + X^2\right)^{0.5}$$

$$A_{\substack{cross\ section \\ channel\ 2}} = 0.5 * L_2 * X$$

$$A_{\substack{cross\ section \\ channel\ 1}} = A_{cross\ section} - A_{\substack{cross\ section \\ channel\ 2}}$$

$$PERIMETER_{channel\ 1} = PERIMETER + 2 * X_3 - L_2$$

$PERIMETER_{channel\ 2} = 2 * X_3 + L_2$

Figure 6. Calculation of Areas and Dimensions for Semicircle Collector.

cost of installing the material but also for the additional materials used to construct the collector (wood, nails, poly-latch, etc). The next set of inputs includes the amount of corn to be dried and the initial and final moisture contents. These moisture contents are given in wet basis. The characteristics of the drying facility are given as bin capacity, bin cross sectional area, initial cost of the fan and initial cost of the heater. Based on the bin capacity and the cross sectional area of the drying bin the depth is found. If the depth is larger than four feet then a message will prompt the user that the maximum depth allowed is four feet.

The size of the fan is determined by the airflow rate. The model suggests an airflow rate of 0.40 $m^3/h\text{-}Kg$ (5 CFM/Bu); however, the model gives the user the option of changing this value. Once the airflow rate is defined then the power required by the fan is calculated. A pressure drop through the collector is assumed to be a maximum of 62.5 Pa (0.25 in. of water). The pressure drop through the grain is calculated by using an equation provided by Hukill and Shedd (1955):

$$P = \frac{a\ Q^2}{\ln(1 + b\ Q)} \tag{17}$$

where

P = pressure drop per foot of grain depth given in inches of water.
Q = airflow rate per square foot of floor area, CFM/ft^2.

a = 0.00065, adimensional.

b = 0.156, adimensional.

The equation is based on curves drawn by Shedd (1953) which are used as standards to calculate pressure drops through different grain types, ASAE Standards (1986). The constants a and b are the intercept and the slope of the curve drawn for corn.

The fan power requirements for driving the air through the collector and then through the grain are calculated separately by using the functions FANCOLLE and FANGRAINE, respectively. The efficiency of the fan is assumed 60%. Once the fan power is calculated the model gives the size of the fan and the user is prompted to estimate the price of the fan. The size of the heater is found by entering the temperature and the airflow rate. An efficiency of 85% for the heater is assumed. The price of the heater is entered next by the user.

Cost of the energy sources are input by the user; however, default values are used in case the user does not desire to enter a value. The energy sources for the fan are assumed to be electricity and LP gas for the heater. Useful life for the fan and the heater are assumed to be 15 years.

Finally, interest on the money invested is input by the user as well as the date to start drying.

Data for ambient conditions are read each time a new batch is going to be dried. Weather data are in English units: horizontal radiation in Btu/ft^2-h, dry bulb temperature in F, wind speed in mph, and relative humidity as a percentage.

Determination of the Incident Angle

The earth moves around the sun in an elliptical orbit with a maximum and minimum distance of 149.68 X 10^6 Km (92.95 X 10^6 mi) and 149.66 X 10^6 Km (92.94 X 10^6 mi) respectively, Kreider and Kreith,1981 p. 2-21). The plane defined by the elliptic path of the earth around the sun is called the ecliptic plane. The angle between this plane and the plane containing the equator is called the declination angle. By convention when this angle points toward north the angle is said to be positive and negative when the sun is located south from the equator. Kreider and Kreith (1981) provide the following equation to calculate this angle within one degree.

$$\sin \delta = 0.39795 \cos[0.98563 (N - 173)] \qquad (18)$$

where

N = day number (usually called Julian day).

δ = declination angle, degrees.

The incident angle is defined as the angle between the sun and an imaginary axes normal to the surface. This angle as well as the rest of the solar angles described below are shown in Figure 7. If the surface is horizontal, the incident angle will be equal to the zenith angle. The incident angle is a function of two other angles, the azimuth and the altitude. These in turn are functions of the latitude, the hour of the day and the declination. When the surface is inclined then two more angles have to be taken into account, the

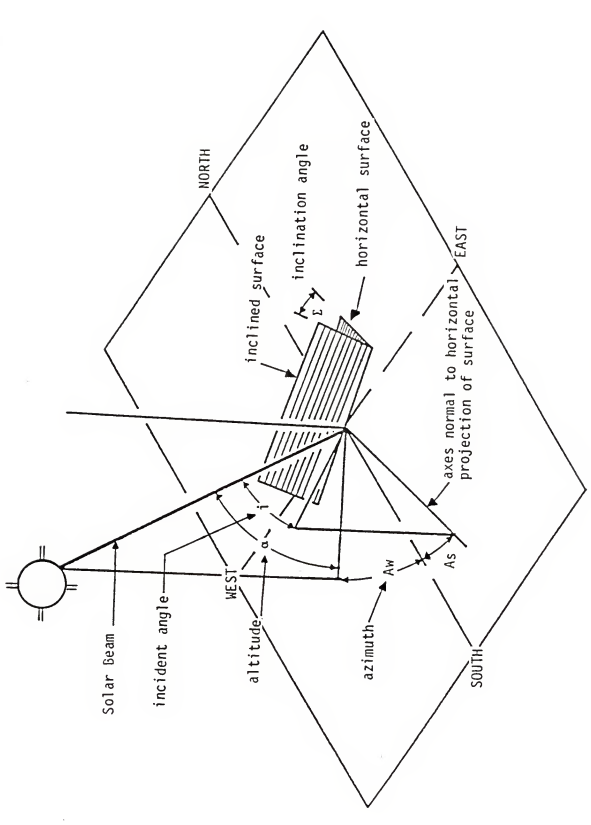


Figure 7. Solar Angles.

inclination of the surface with respect to a horizontal surface and the orientation. The orientation angle is the horizontal angle between the south and axes normal to the collector surface. This angle is measured from south to east (counterclockwise). Equation (19) is used to calculate the altitude:

$$\sin \alpha = \cos L \cos \delta \cos Hs + \sin L \sin \delta \qquad (19)$$

where

α = altitude.

L = latitude.

Hs= hour angle.

The hour angle is the hour expressed in degrees. By convention solar noon is the hour 0 degrees. The day is divided into 24 hours in which the earth describes a circle of 360 deg. Dividing 360 degrees by 24 hours we obtain 15 degrees per hour. By convention the hours before solar noon are positive and the hours in the afternoon are negative. The azimuth angle is calculated as follows:

$$\sin As = \frac{\cos \delta \sin Hs}{\cos \alpha} \qquad (20)$$

where As = azimuth.

To find the true angle, however, one has to determine whether the sun is north or south from the desired location. The following rule is used to determine the true azimuth angle.

$$\text{if } \cos Hs > \frac{\text{Tan } \alpha}{\text{Tan } L}$$

then

$$As = \sin^{-1} \left(\frac{\cos \alpha \sin Hs}{\cos \alpha} \right) \qquad (21\text{-A})$$

$$\text{If } \cos Hs < \frac{\text{Tan } \alpha}{\text{Tan } L}$$

$$As = 180 - \sin^{-1} \left(\frac{\cos \alpha \sin Hs}{\cos \alpha} \right) \qquad (21\text{-B})$$

$$\text{If } \cos Hs = \frac{\text{Tan } \alpha}{\text{Tan } L}$$

then

$$As = 90 \text{ , if } \cos Hs >= 0 \qquad (21\text{-C})$$

$$As = -90 \text{ , if } \cos Hs < 0 \qquad (21\text{-D})$$

where

As = Azimuth angle.

Hs = Hour angle.

L = Latitude.

α = Altitude angle.

δ = Declination angle

Sunrise is determined by using the equation for the altitude. At sunrise the altitude is zero so solving for the hour angle one obtains the following expression:

$$Hsr = \cos^{-1} (- \text{Tan } L \text{ Tan } \delta) \qquad (22)$$

where Hsr = sunrise hour angle.

The sunset is determined by using the same hour angle and changing the sign.

Once found the incident angle can be calculated.

$$\cos i = \cos \alpha \cos(As - Aw) \sin \Sigma + \sin \alpha \cos \Sigma \qquad (23)$$

where

Aw = orientation angle.

Σ = inclination angle.

If the right side of this equation is negative, then the sun will not strike the surface until i = 90. The sunrise and sunset could be calculated by stating the equation,

$$\cos (As - Aw) = - \text{Tan } \alpha \text{ Cot } \Sigma \qquad (24)$$

Determination of Direct and Diffuse Radiation

Even though the low temperature air-type solar collector uses both direct and diffuse radiation, it is important to differentiate between these two types in order to calculate the energy transmitted through the cover. For diffuse radiation Robbins and Spillman (1980) recommends an incident angle of 60 degrees for any cover

orientation. The incident angle for direct radiation is calculated hourly following the procedure shown previously. An algorithm presented by Kreider and Kreith (1981) and developed by Randall and Whitson (1977) is used to determine the amount of direct and diffuse radiation. The algorithm developed is based on data in five different locations with dissimilar climates. These places were U.S. Livermore, California; Raleigh, No. Carolina; Ft. Hood, Texas; Maynard, Massachussets and Albuquerque, New Mexico. Direct and total horizontal radiation data were collected and plotted in graphs as the percentage of total possible radiation (k_T) versus the percentage of possible direct radiation (k_B). The graph and data shown in figure 8 were used in this model to determine the amount of direct and diffuse radiation. This graph is a piecewise approximation of the data collected on these five cities.

To determine the total possible radiation value K_T it is necessary to know the extraterrestrial direct radiation. This is the radiation per unit area falling on a normal surface above the atmosphere. This value varies with the earth-sun distance. The routine DAYNUM provides an average value for each month. Below are the equations used to determine the amount of direct and diffuse radiation falling on an inclined surface.

$$K_T = \frac{I_H}{Iext \sin \alpha} \tag{25}$$

$$K_B = A_i K_T + B_i \tag{26}$$

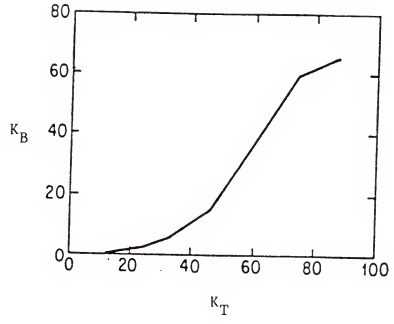


Figure 8. Percent of Direct Radiation K_B as a Function of the Percent of Total Horizontal Radiation K_T (Kreider and Kreith, 1981, p. 2-67).

Table 1. Coefficients for the Piecewise Linear Function $K_B = A_i K_T + B_i$.

Interval for K_T	A_i	B_i
0.00, 0.05	0.04	0.00
0.05, 0.15	0.01	0.002
0.15, 0.25	0.06	-0.006
0.25, 0.35	0.32	-0.071
0.35, 0.45	0.82	-0.246
0.45, 0.55	1.56	-0.579
0.55, 0.65	1.69	-0.651
0.65, 0.75	1.49	-0.521
0.75, 0.85	0.27	0.395

Source: Kreider and Kreith (1981, p. 2-67).

and

$$K_B = \frac{I_B}{Iext} \tag{27}$$

Then

$$I_B = K_B \, Iext \tag{28}$$

The diffuse radiation, I_d can be calculated as follows:

$$I_d = I_H - I_B \tag{29}$$

where

A_i and B_i = Coefficients of the piecewise equation (see Figure 8).

I_B = Direct radiation incident on a horizontal surface.

I_{ext} = Direct radiation normal to a surface above the atmosphere.

I = Total horizontal radiation.

K_B = Percentage of direct radiation falling on a horizontal surface.

K_T = Percentage of the total possible.

The next step would be to calculate the amount of direct and diffuse radiation incident on the cover surface.

$$I_{Bt} = I_B \cos (i) \tag{30}$$

$$I_{dt} = Fss\ I_d + Fsg\ \rho_{ground}\ I_B \tag{31}$$

where

Fss = Angle factor between the cover surface and the sky.

Fsg = Angle factor between the cover and the the ground.

I_{Bt} = Direct radiation incident on the collector surface.

I_{dt} = Diffuse radiation incident on the collector surface.

$$Fss = \frac{1 + \cos (\Sigma)}{2} \tag{32}$$

$$Fsg = \frac{1 - \cos (\Sigma)}{2} \tag{33}$$

The reflectance of the ground is reported to be between 10 and 20 percent (ASHRAE FUNDAMENTALS, 1976, Kreider and Kreith, 1981). Robins and Spillman (1980) found 20 percent a more reasonable value for either live or death vegetation. This last value is used in the model.

Collector Analysis

The analysis of collector performance requires the determination of outlet air temperature, thermal efficiency of the collector and useful heat recovered by the air. Chau (1981) presented a method for the determination of the outlet air temperature. This method is based

on heat balance equations on each layer of the collector, i.e. for a single cover collector with air flowing above the absorber two layers are found, the cover and the absorber. A heat balance equation on the air flowing through the collector is also written. The average fluid temperature is written in terms of absorber, cover and inlet air temperature. The heat balance equations for each layer and the average air temperature written in terms of the mentioned variables results in equations of the form.

$$F_1(T_1,T_2) = A_{11}\,T_1^4 + A_{12}\,T_2^4 + B_{11}\,T_1 + B_{12}\,T_2 + C_1 \qquad (34\text{-A})$$

$$F_2(T_1,T_2) = A_{21}\,T_1^4 + A_{22}\,T_2^4 + B_{21}\,T_1 + B_{22}\,T_2 + C_2 \qquad (34\text{-B})$$

These equations are solved using the Newton-Raphson method for a nonlinear system of equations. This method is described in appendix I. Figure 9 shows a flow diagram of the subroutine PERFORMANCE used to simulate collector performance, the derivation of the first set of equations is shown here as an example. The other derivations are presented in Appendices A and B.

Collector Type I

Figure 10 shows the heat interactions in a section area of collector type I. The equations for these heat interactions are shown below. q_0 to q_{13} refers to the heat interactions shown on Figure 10. The subscripts 1 and 2 identify the properties for the cover and the absorber, respectively.

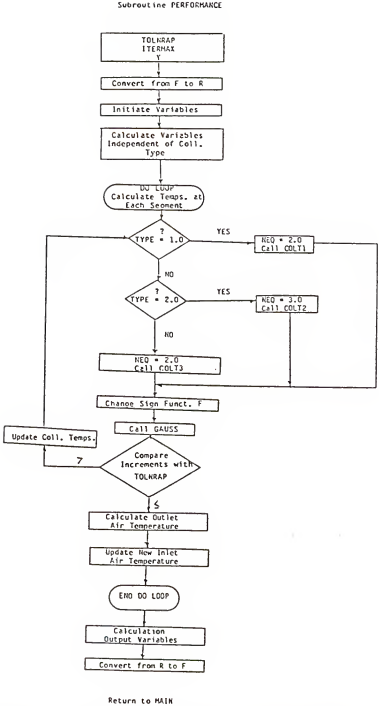


Figure 9. Flowchart of Subroutine PERFORMANCE.

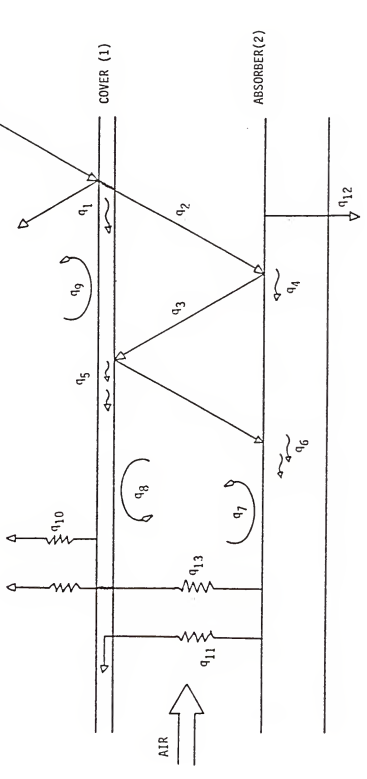


Figure 10. Schematic Diagram of the Heat Balances on Collector Type I.

$$q_1 = A_4 \, \alpha_{1S} \, q_0 \tag{35}$$

$$q_4 = \alpha_{2S} \, \tau_{1S} \, q_0 \tag{36}$$

$$q_5 = \alpha_{1s} \, \rho_{12S} \, \tau_{1S} \, q_0 \tag{37}$$

$$q_6 = \alpha_{2S} \, \rho_{1S} \, \tau_{1S} \, \rho_{12S} \, q_0 \tag{38}$$

$$q_7 = h_2 \, (T_2 - T_f) \tag{39}$$

$$q_8 = A_4 \, h_1 \, (T_1 - T_f) \tag{40}$$

$$q_9 = A_4 \, h_w \, (T_1 - T_a) \tag{41}$$

$$q_{10} = A_4 \, \sigma \, \varepsilon_{1L} \, (T_1^4 - T_{sky}^4) \tag{42}$$

$$q_{11} = \sigma \, \varepsilon_{12L} \, (T_2^4 - T_1^4) \tag{43}$$

$$q_{12} = \frac{A_5}{R_B} \, (T_2 - T_a) \tag{44}$$

$$q_{13} = \sigma \, \varepsilon_{2L} \, \tau_{1L} \, (T_2^4 - T_{sky}^4) \tag{45}$$

where

q_0 = total, direct and incident solar energy incident on the collector surface.

q_1 = solar energy absorbed by the cover.

q_4 = solar energy absorbed by the absorber.

q_5 = total solar energy reflected by the absorber and absorbed by the cover.

q_6 = total reflecting energy absorbed by the absorber.

q_7 = heat exchange between the air going through the collector and the absorber.

q_8 = heat exchange between the air going through the collector and the cover.

q_9 = heat exchange between the cover and the outside air.

q_{10} = heat lost from the cover to the sky by radiation.

q_{11} = net heat radiated from the absorber to the cover.

q_{12} = heat lost from the absorber through the bottom.

q_{13} = net heat radiated from the absorber to the sky.

A_4 = cover area divided by the absorber area.

A_5 = bottom area divided by absorber area.

R_B = thermal resistance of the bottom of the collector.

ε_{12L} = emissivity function between the cover and the absorber for the longwavelength range.

ρ_{12S} = reflectivity factor between the cover and the absorber for the short wavelength range.

All these equations have been divided by the absorber area. The equations containing the absorber area will then have a factor of one. q_9 contains the film convection coefficient between the outside surface of the cover and the ambient air. This film convection coefficient is found by using an empirical equation (Duffie and Beckman, 1974, p.76).

$$h_w = 5.7 + 3.8\ V \tag{46}$$

where V is the air velocity in meters per second and h_w is given in watts per square meter-degree C. The coefficients of this equation were adjusted so the velocity could be read in miles per hour and the convection film coefficient would be in Btu per hour square foot-degree F. The temperature of the sky was also estimated with an empirical equation (Duffie and Beckman, 1974, p.76).

$$T_{sky} = 0.0552\ T_a^{1.5} \tag{47}$$

Again this temperature is given in degrees Kelvin and the equation is modified so T_a and T_{sky} are in degrees Rankine. The thermal resistance, R_B, is calculated as follows.

$$R_B = \text{insulation resistance} + 1/h_B \tag{48}$$

$$h_B = 0.37\ \text{Btu/ ft}^2\text{-h-F} \tag{49}$$

This film convection coefficient is proposed by ASHRAE (1981, p. 23-12) for still air on a horizontal surface facing downward and with surface emittance of 0.20. Usually the boxes of the air-type solar collectors are constructed of plywood one centimeter thick (0.375 in). Wood emittance varies between 0.25 and 0.30. Thermal

resistance of the plywood is 0.08 m^2-C/w(0.47 h-ft^2-F/Btu) which is small compared to the resistance due to the insulation and convection on the outside wall (about 0.7 m^2-K/w) so it has been neglected.

Emissivity factor between the cover and the absorber

Figure 11 shows the energy radiated by the absorber. Part of this energy is transmitted through the cover and lost to the sky, another part is absorbed by the cover and the remaining is reflected back to the absorber. The absorber and cover are considered gray bodies, then the absorptivity is equal to the emissivity within the same wavelength range. The sum of the energy lost from the absorber to the sky can be written as follows:

$$q_{2\text{-sky}} = \sigma T_2^4 \varepsilon_{2L} \tau_{1L} (1 + (1 - \tau_{1L} - \varepsilon_{1L})(1 - \varepsilon_{2L}) + (1 - \tau_{1L} - \varepsilon_{1L})^2 (1 - \varepsilon_{2L})^2 + \ldots) \quad (50)$$

This is a geometric series with a sum that converges to the following expression:

$$q_{2\text{-sky}} = \sigma \varepsilon_{2L} \tau_{1L} T_2^4 + \sigma \varepsilon_{2L} \tau_{1L} \frac{(1 - \tau_{1L} - \varepsilon_{1L})(1 - \varepsilon_{2L})}{(1 - (1 - \tau_{1L} - \varepsilon_{1L})(1 - \varepsilon_{2L}))} T_2^4 \quad (51)$$

The heat radiated from the sky to the cover is

$$q_{\text{sky-2}} = \sigma \varepsilon_{2L} \tau_{1L} T_{\text{sky}}^4 \quad (52)$$

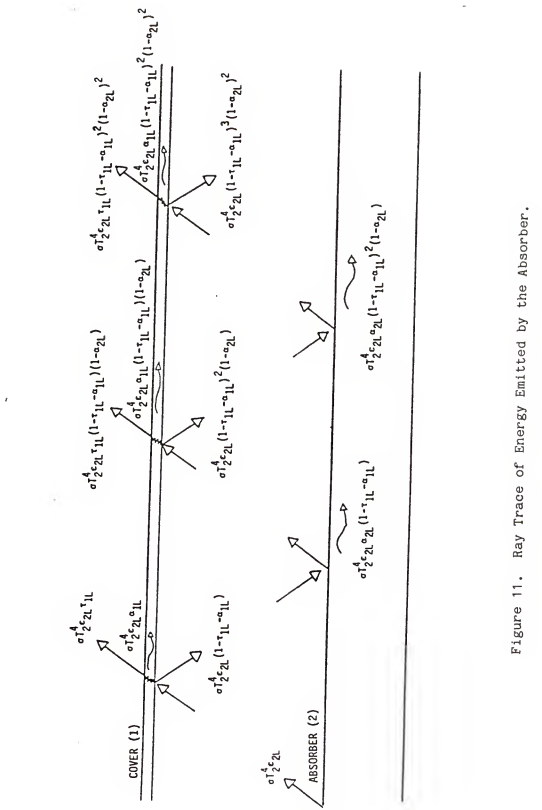


Figure 11. Ray Trace of Energy Emitted by the Absorber.

The net heat losses from the absorber to the sky, q_{13}, is equal to the following expression:

$$q_{2\text{-sky}} - q_{\text{sky-2}} = \sigma\, \varepsilon_{2L}\tau_{1L}T_2^4 + \sigma\, \varepsilon_{2L}\tau_{1L}\, \frac{(1 - \tau_{1L}-\varepsilon_{1L})(1 - \varepsilon_{2L})}{(1 - (1 - \tau_{1L}-\varepsilon_{1L})(1 - \varepsilon_{2L}))}\, T_2^4 \tag{53}$$

The second factor on the right needs some analysis. The absorber emissivity is always close to one (on the menu provided in the model the lowest value is 0.9). By using the assumption that the emissivity of the cover is equal to one minus τ_{1L} divided by two, a sensitivity analysis was done and found that the factor grows with τ_{1L} and with a low ε_{2L}. Using the combination that provides the highest value for this factor (emissivity of the absorber equal 0.9 for polyethylene and the transmissivity of the transparent plastic, 0.8, both properties for the long wavelength) the error obtained when not considering this factor is about 6%. This error, however, when compared with the overall losses of the collector, is negligible and hence, q_{13}, which is the heat loss between the absorber and the sky does not consider this factor.

The heat lost from the absorber to the cover is the sum of the terms of the second line in Figure 11. Note that α_{1L} is equal to ε_{1L}. The sum is also a geometric series which converges to the following expression:

$$q_{2\text{-}1} = \sigma\, \frac{\varepsilon_{1L}\, \varepsilon_{2L}}{(1 - (1 - \tau_{1L} - \varepsilon_{1L})\,(1 - \varepsilon_{2L}))}\, T_2^4 \tag{54}$$

The heat radiated from the cover to the absorber is shown on the bottom line of Figure 12. Again the sum is a geometric series and since $\alpha_{2L} = \varepsilon_{2L}$,

$$q_{1-2} = \frac{\sigma\, \varepsilon_{1L}\, \varepsilon_{2L}}{1 - (1 - \tau_{1L} - \varepsilon_{1L})\,(1 - \varepsilon_{2L})}\, T_2^4 \qquad (55)$$

The net energy lost is equal to q_{11}:

$$q_{2-1} - q_{1-2} = \sigma\, \frac{\varepsilon_{1L}\, \varepsilon_{2L}}{(1 - (1 - \tau_{1L} - \varepsilon_{1L})\,(1 - \varepsilon_{2L})}\, (T_2^4 - T_1^4) \qquad (56)$$

where the emissivity function, ε_{12L}, is

$$\varepsilon_{12L} = \frac{\varepsilon_{1L}\, \varepsilon_{2L}}{(1 - (1 - \tau_{1L} - \varepsilon_{1L})\,(1 - \varepsilon_{2L}))} \qquad (57)$$

Derivation of ρ_{12S} factor

Once the solar radiation enters the collector through the cover, the energy is either absorbed by the absorber or reflected to the cover. The reflected energy can be absorbed, transmitted through the cover or reflected back to the absorber. q_5 and q_6 determine the amount of energy that stays in the collector. q_5 is the total solar energy absorbed by the cover after it enters the collector. This total energy can be written as an infinite series:

$$q_5 = \tau_{1S}\, q_0\, \rho_{2S}\, \alpha_{1S} + \tau_{1S}\, q_0\, \rho_{1S}\, \rho_{2S}^2\, \alpha_{1S} + \tau_{1S}\, q_0\, \rho_{1S}^2\, \rho_{2S}^3 + \cdots \qquad (58)$$

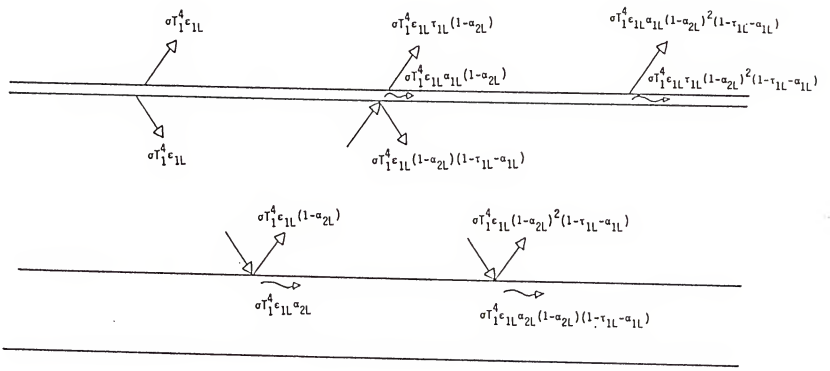

$\sigma T_1^4 \epsilon_{1L}$
$\sigma T_1^4 \epsilon_{1L} \tau_{1L} (1-\alpha_{2L})$
$\sigma T_1^4 \epsilon_{1L} \alpha_{1L} (1-\alpha_{2L})^2 (1-\tau_{1L}-\alpha_{1L})$
$\sigma T_1^4 \epsilon_{1L} \alpha_{1L} (1-\alpha_{2L})$
$\sigma T_1^4 \epsilon_{1L} \tau_{1L} (1-\alpha_{2L})^2 (1-\tau_{1L}-\alpha_{1L})$
$\sigma T_1^4 \epsilon_{1L}$
$\sigma T_1^4 \epsilon_{1L} (1-\alpha_{2L}) (1-\tau_{1L}-\alpha_{1L})$
$\sigma T_1^4 \epsilon_{1L} (1-\alpha_{2L})$
$\sigma T_1^4 \epsilon_{1L} (1-\alpha_{2L})^2 (1-\tau_{1L}-\alpha_{1L})$
$\sigma T_1^4 \epsilon_{1L} \alpha_{2L}$
$\sigma T_1^4 \epsilon_{1L} \alpha_{2L} (1-\alpha_{2L}) (1-\tau_{1L}-\alpha_{1L})$

Figure 12. Ray Trace of Energy Emitted by the Cover to the Sky and to the Absorber.

The factors of this series have the same sequence as the series shown previously and converge to the following expression:

$$q_5 = \tau_{1S}\, q_0\, \frac{\rho_{2S}\, \alpha_{1S}}{(1 - \rho_{1S}\, \rho_{2S})} \tag{59}$$

grouping terms in equation (59) such that

$$\rho_{12S} = \frac{\rho_{2S}}{(1 - \rho_{1S}\, \rho_{2S})} \tag{60}$$

where q_4 is the energy absorbed by the absorber the first time the solar rays strike it and q_6 is the energy absorbed after these rays reflect to the cover and from the cover, back to the absorber. The expression that accounts for the energy absorbed after all the reflections is shown below.

$$q_6 = \tau_{1S}\, q_0\, \rho_{2S}\, \rho_{1S}\, \alpha_{2S} + \tau_{1S}\, q_0\, \alpha_{2S}\, \rho_{1S}^2\, \rho_{2S}^2 + \cdots \tag{61}$$

Factorizing this series and using ρ_{12S} factor, the equation above can be simplified.

$$q_6 = \tau_{1s}\, q_0\, \alpha_{2s}\, \rho_{1s}\, \rho_{12S} \tag{62}$$

Assumptions and determination of unknown optical properties

Table 2 shows the optical properties known and unknown from the cover and absorber. It is difficult to find optical properties in the long wavelength so some assumptions have to be made.

Table 2. Known and Unknown Optical Properties of Collectors.

	Short Wavelength			Long Wavelength		
	ρ	τ	α	ρ	τ	α
Cover	unknown	known	unknown	unknown	known	unknown
Absorber	known	known	known	unknown	known	known

Two considerations are important for finding the unknown properties, one is the Kirckoff's law which states that the emissivity should be equal to the absorptivity if they are for the same wavelength (or, practically speaking, if they are in the same wavelength range). The second consideration is the sum of the reflectivity, transmissivity and absorptivity must be equal to one.

From Table 2 one can see that all the optical properties for the absorber are readily available; however, some assumptions have to be made for the cover. The cover's transmissivity for solar radiation should be very high, ideally one, hence the reflectivity and absorptivity are very small. The value of these two properties is assumed to be equal.

The same assumption is made for the long wavelength properties. Even though the transmissivity will not necesarilly be large the effects of having higher or lower absorptivity will not produce a big error. Homan et al. (1981) suggests the use of a low value for the long wavelength emissivity which would be a less conservative assumption.

Data for the optical properties of the cover were taken from Godbey et al. (1977). Transmissivity in the solar wavelength range was given for six different incident angles for each cover material. These values were fitted into nonlinear functions. These functions are shown in Appendix C. Other data provided by Godbey are average short wavelength and long wavelength transmissivity. Godbey's data compared favorably with some other sources (Kreider and Kreith, 1981, and Homann et al., 1981). Optical properties for the absorber were taken from Kreider and Kreith (1981) and Homann et al. (1981). The lists of materials as they appear on the computer screen are shown on Appendix D.

Film convection coefficient

For the purposes of calculating convection coefficients air-type solar collectors are usually considered as ducts even though these have different cross sectional areas and the heat is coming only from one side. Parker (1981a) presented the following set of equations to calculate the Nusselt number.

$$Nu = 0.344\ Re^{0.35} \quad \text{for } 100 \leq Re \leq 2100 \qquad (65\text{-A})$$

$$Nu = 168 \times 10^{-9} Re^{2.25} \quad \text{for } 2100 \leq Re \leq 2850 \qquad (65\text{-B})$$

$$Nu = 2.55 \times 10^{-3} Re^{1.04} \quad \text{for } 2850 \leq Re \leq 5650 \qquad (65\text{-C})$$

$$Nu = 19.8 \times 10^{-3}\ Re^{0.8} \quad \text{for } 5650 \leq Re \leq 1000{,}000 \qquad (65\text{-D})$$

Once having the Nusselt number, the convection coefficient (h) can be calculated:

$$h = \frac{N_u K}{D_e} \tag{66}$$

where

K = Thermal conductivity of the air.

D_e = Hydraulic diameter of cross sectional shape.

$$Re = \frac{\rho_{air} D_e V}{\mu} \tag{67}$$

$$D_e = \frac{4 \text{ X cross sectional area}}{\text{perimeter}} \tag{68}$$

A commonly used equation to calculate the Nusselt number is presented by Holman (1981, p.226),

$$Nu = 0.023 \, Re^{0.8} \, Pr^{0.4} \tag{69}$$

Where Pr is the Prandtl number and is constant within the temperature range of air-type solar collectors (Pr = 0.7). Tan and Charters (1969) and Chau, (1981) used this Reynolds-Nusselt relationship for fully developed flow. For the entrance they used a local Nusselt number calculated by the following empirical equation:

$$Nu_{local} = (1.78 - 0.0864\ (L / D_e)^{0.53})\ Nu_{\infty} \qquad (70)$$

where L = distance from the air entrance.

Nu_{∞} is calculated with the Reynolds-Nusselt relationship shown above. These equations have proven to be adequate for low-profile cross sectional areas, i.e., small distance between the absorber and the cover. However, some collectors have considerably higher distance between absorber and cover, e.g., Talbot and Elfino (no date a,b) tested collectors one meter high (3 ft) and higher. For these collectors the air velocity through the collector is small. It was decided that the empirical relationship for convection on a flat plate would give better results. This is the same relationship that is used for the film convection coefficient between the cover and the ambient air equation (46). This equation was used when the height of the collector was over 0.3 meters (1 ft) for type I collectors. It is important to mention that the equations given by Parker were giving very close results compared to the Reynolds-Nusselt relationship; however, since the former equation is widely known it was preferred over Parker's.

Development of the final equation for collector type I

Figure 10 shows the profile diagram of the collector type I. A heat balance equation on the cover will give the following expression:

$$q_1 + q_5 + q_{11} = q_8 + q_9 + q_{10} \qquad (71)$$

Heat balance on the absorber gives

$$q_4 + q_6 = q_7 + q_{11} + q_{12} + q_{13} \tag{72}$$

By looking at the equations (35) through (45) presented at the beginning of this section, one can see that the temperature of the absorber, cover and fluid going through the collector are unknown so another equation is necessary. An energy balance is done on the air going through the collector (see Figure 13).

$$GC_p(T_{out} - T_{in}) = \frac{A_2}{N_0} (A_4 h_1 (T_1 - T_f) + h_2 (T_2 - T_f)) \tag{73}$$

Subscripts 1 and 2 identify the cover and absorber respectively, G is the air mass flow rate, the subscrips in and out are for the air coming in and the air going out of the segment analyzed. The collector is divided into N_0 segments and in each one the unknown temperatures are determined.

In equation (73) one more unknown appears that is the outlet air temperature. The inlet temperature is known either by the segment previously analyzed or for the first segment the temperature would be equal to the ambient temperature. To solve for the outlet air temperature it is assumed that the fluid temperature is the arithmetic average of the inlet and outlet air temperatures,

$$T_f = \frac{T_{out} + T_{in}}{2} \tag{74}$$

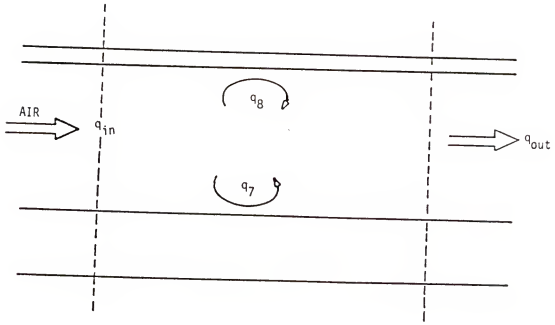


Figure 13. Energy Balance on Fluid, Collector Type I.

then

$$T_{out} = 2\,T_f - T_{in} \tag{75}$$

The heat balance equation can be written as follows:

$$\frac{2\,G\,C_p}{A_6}(T_f - T_{in}) = A_4\,h_1\,(T_1 - T_f) + h_2\,(T_2 - T_f) \tag{76}$$

A_6 is the absorber area divided by the number of segments, N_0. A_4 is the ratio between the area of the cover and the absorber area. The average air temperature can be written in terms of the inlet air temperature and the cover and absorber temperature.

$$T_f = \frac{\frac{2\,G\,C_p}{A_6}\,T_{in} + A_4\,h_1\,T_1 + h_2\,T_2}{\frac{2\,G\,C_p}{A_6} + A_4\,h_1 + h_2} \tag{77}$$

Writing the heat balance on the cover

$$A_4\,\alpha_{1S}\,q_0 + A_4\,\alpha_{1S}\,\rho_{12S}\,\tau_{1S}\,q_0 + \sigma\,\varepsilon_{12L}\,(T_2^4 - T_1^4) =$$

$$A_4\,h_1\,(T_1 - T_f) + A_4\,h_w\,(T_1 - T_a) + A_4\,\sigma\,\varepsilon_{1L}(T_1^4 - T_{sky}^4) \tag{78}$$

Rearranging

$$\sigma\,(A_4 + \varepsilon_{12L})\,T_1^4 - \sigma\,\varepsilon_{12L}\,T_2^4 + A_4\,(h_1 + h_w)\,T_1 -$$

$$A_4\,(h_1\,T_f + h_w\,T_a + \sigma\,\varepsilon_{1L}\,T_{sky}^4 + \alpha_{1S}\,q_0 - \alpha_{1S}\,\rho_{12S}\,\tau_{1S}\,q_0) = 0 \tag{79}$$

Replacing T_f by equation (77) and rearranging

$$\sigma (A_4 \varepsilon_{1L} + \varepsilon_{12L}) T_1^4 - \sigma \varepsilon_{12L} T_2^4 + \left(A_4 (h_1 + h_w) - \frac{A_4^2 h_1^2}{D}\right) T_1 -$$

$$\left(\frac{A_4 h_1 h_2}{D}\right) T_2 - A_4 h_1 \frac{\frac{2 G C_P}{A_6}}{D} T_{in} - A_4 h_w T_a -$$

$$A_4 (\sigma \varepsilon_{1L} T_{sky}^4 + \alpha_{1S} q_0 + \alpha_{1S} \rho_{12S} \tau_{1S} q_0) = 0 \qquad (80)$$

where

$$D = \frac{2GC_P}{A_6} + A_4 h_1 + h_2 \qquad (81)$$

Writing heat balance on the absorber

$$\alpha_{2S} \tau_{1S} q_0 (1 + \rho_{1S} \rho_{12S}) = h_2 (T_2 - T_f) + \sigma \varepsilon_{12L} (T_2^4 - T_1^4) +$$

$$\frac{A_5}{R_B} (T_2 - T_a) + \sigma \varepsilon_{2L} \tau_{1L} (T_2^4 - T_{sky}^4) \qquad (82)$$

Rearranging

$$\sigma \varepsilon_{12L} T_1^4 - \sigma (\varepsilon_{12L} + \varepsilon_{2L} \tau_{1L}) T_2^4 - \left(h_2 + \frac{A_5}{R_B}\right) T_2 +$$

$$\alpha_{2S} \tau_{1S} q_0 (1 + \rho_{1S} \rho_{12S}) + \sigma \varepsilon_{2L} \tau_{1L} T_{sky}^4 + \frac{A_5}{R_B} T_a + h_2 T_f = 0 \qquad (83)$$

Rearranging and replacing T_f by equation (77)

$$\sigma \varepsilon_{12L} T_1^4 - \sigma (\varepsilon_{12L} + \varepsilon_{2L} \tau_{1L}) T_2^4 + \frac{A_4 h_1 h_2}{D} T_1 -$$

$$(h_2 + \frac{A_5}{R_B} - \frac{h_2^2}{D}) T_2 + \alpha_{2S} \tau_{1S} q_0 (1 + \rho_{1S} \rho_{12S}) +$$

$$\sigma \varepsilon_{2L} \tau_{1L} T_{sky}^4 + \frac{A_5}{R_B} T_a + h_2 \frac{\frac{2 G C_p}{A_6}}{D} T_{in} = 0 \qquad (84)$$

Equations (80) and (84) can be written as follows:

$$F_1(T_1,T_2) = a_{11} T_1^4 + a_{12} T_2^4 + b_{11} T_1 + b_{12} T_2 + c_1 = 0 \qquad (85\text{-A})$$

$$F_2 (T_1,T_2) = a_{21} T_1^4 + a_{22} T_2^4 + b_{21} T_1 + b_{22} T_2 + c_2 = 0 \qquad (85\text{-B})$$

where

$$a_{11} = \sigma (A_4 \varepsilon_{1L} + \varepsilon_{12L}) \qquad (86)$$

$$a_{12} = -\sigma \varepsilon_{12L} \qquad (87)$$

$$b_{11} = A_4 (h_1 + h_w) - \frac{A_4^2 h_1^2}{D} \qquad (88)$$

$$b_{12} = - \frac{A_4 h_1 h_2}{D} \qquad (89)$$

$$c_1 = -A_4 \left[h_1 \frac{\frac{2\ G\ C_p\ T_{in}}{A_6}}{D} + h_w\ T_a + \sigma\ \varepsilon_{1L}\ T_{sky}^4 + \right.$$

$$\left. \alpha_{1S}\ q_0\ (1 + \rho_{12S}\ \tau_{1S}) \right] \tag{90}$$

$$a_{21} = \sigma\ \varepsilon_{12L} \tag{91}$$

$$a_{22} = -\ \sigma\ (\varepsilon_{12L} + \varepsilon_{2L}\ \tau_{1L}) \tag{92}$$

$$b_{21} = \frac{A_4\ h_1\ h_2}{D} \tag{93}$$

$$b_{22} = -\left[\frac{A_5}{R_B} + h_2\ (1 - \frac{h_2}{D}) \right] \tag{94}$$

$$c_2 = \alpha_{2S}\ \tau_S\ q_0 (1 + \rho_{1S}\ \rho_{12S}) + \sigma\ \varepsilon_{2L} \tau_{1L}\ T_{sky}^4 + \frac{A_5\ T_a}{R_B} +$$

$$h_2 \frac{\frac{2\ G\ C_p}{A_6}}{D}\ T_{in} \tag{95}$$

Collector Type II

A diagram showing the heat balances on collector type II is shown in Figure 14. The equations and the derivation of the final functions are shown in Appendix A. In this collector type there are five unknown temperatures so five equations have to be stated. These are the cover, absorber and bottom temperatures, and the air temperatures going through channels one and two. Heat balances are written on the cover, absorber and bottom and on each channel. The assumptions are

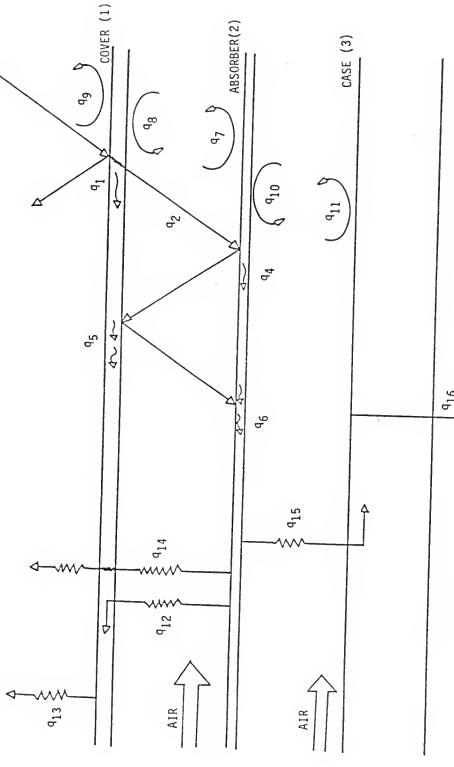


Figure 14. Schematic Diagram of Heat Balances on Collector Type II.

basically the same as those used for the derivation of the collector type I. These assumptions are stated again during the derivation of this collector type. In this part the calculation of the film convection coefficient between the absorber and the air channel 2 and the film convection coefficient between the bottom and the air going through channel 2 is going to be shown. The determination of these two parameters is slightly different from collector type I.

The bottom is assumed to be well insulated so the temperature of the bottom will always be higher than the temperature of the air going through channel 2. Fitzgibbons and Kline (1978) used an equation proposed by Kays (1966) for film convection coeffficients between two hot parallel plates with air going between. Fitzgibbons and Kline (1978), in their model for a suspended plate collector, modified an equation for the film convection coefficients proposed by Kays:

$$Nu_2 = N_u \frac{1 + (\frac{T_3 - T_{f2}}{T_2 - T_{f2}})\,\theta}{1 - \theta^2} \qquad (96)$$

$$Nu_3 = N_u \frac{1 + (\frac{T_2 - T_{f2}}{T_3 - T_{f2}})\,\theta}{1 - \theta^2} \qquad (97)$$

where

$$\theta = 0.570\ Re^{-0.106}$$

The factor θ is a tabulated quantity called the influence coefficient. The value of Nu is calculated using Holman and Tan and

Charters (1969) equations as was previously shown for collector type I.

The emissivity factors used for the upper part of the absorber (channel 1) between the cover and the sky, between the absorber and the sky and between the cover and the absorber are the same as for collector type I; however, the emissivity factor between the absorber and the bottom is slightly different than from the absorber and the cover. The reason is because there is no transmissivity on the bottom or on the absorber. The emissivity factor will be equal to the following equation:

$$\varepsilon_{23L} = \frac{1}{\frac{1}{\varepsilon_{2L}} + \frac{1}{\varepsilon_{3L}}} \tag{99}$$

The final equations are shown below.

$$F_1(T_1, T_2, T_3) = a_{11}T_1^4 + a_{12}T_2^4 + a_{13}T_3^4 + b_{11}T_1 + b_{12}T_2 + b_{13}T_3 + c_1 = 0 \tag{100}$$

$$F_2(T_1, T_2, T_3) = a_{21}T_1^4 + a_{22}T_2^4 + a_{23}T_3^4 + b_{21}T_1 + b_{22}T_2 + b_{23}T_3 + c_2 = 0 \tag{101}$$

$$F_3(T_1, T_2, T_3) = a_{31}T_1^4 + a_{32}T_2^4 + a_{33}T_3^4 + b_{31}T_1 + b_{32}T_2 + b_{33}T_3 + c_3 = 0 \tag{102}$$

where

$$a_{11} = \sigma (A_4 \varepsilon_{1L} + \varepsilon_{12L}) \tag{103}$$

$$a_{12} = - \sigma \varepsilon_{12L} \tag{104}$$

$$a_{13} = 0 \tag{105}$$

$$b_{11} = A_4 \left(h_1 + h_w - \frac{A_4 h_1^2}{D_1}\right) \tag{106}$$

$$b_{12} = - A_4 \frac{h_1 h_2'}{D_1} \tag{107}$$

$$b_{13} = 0 \tag{108}$$

$$c_1 = - A_4 \left\{\alpha_{1S} (q_0 + \rho_{12S} \tau_{1S} q_0) + h_w T_a + \sigma \varepsilon_{1L} T_{sky}^4 + h_1 \frac{2 G_1 C_p T_{in1}}{D_1}\right) \tag{109}$$

$$a_{21} = \sigma \varepsilon_{12L} \tag{110}$$

$$a_{22} = - \sigma (\varepsilon_{12L} + \varepsilon_{23L} + \tau_{1L} \varepsilon_{2L}) \tag{111}$$

$$a_{23} = \sigma \varepsilon_{23L} \tag{112}$$

$$b_{21} = \frac{A_4 \; h_1 \; h'_2}{D_1} \tag{113}$$

$$b_{22} = -\left(h'_2 + h''_2 - \frac{h'^2_2}{D_1} - \frac{h''^2_2}{D_2}\right) \tag{114}$$

$$b_{23} = \frac{A_5 \; h''_2 \; h_3}{D_2} \tag{115}$$

$$c_2 = \alpha_{2S} \; \tau_{1S} \; q_0 \; (1 + \rho_{1S} \; \rho_{12S}) + \sigma \; \tau_{1L} \varepsilon_2 T_{sky}^4 + \frac{\dfrac{h'^2_2 \; G_1 \; C_p \; T_{in1}}{A_6}}{D_1} + \frac{\dfrac{h''^2_2 \; G_2 \; C_p \; T_{in2}}{A_6}}{D_2} \tag{116}$$

$$a_{31} = 0 \tag{117}$$

$$a_{32} = \sigma \; \varepsilon_{23L} \tag{117}$$

$$a_{33} = -\sigma \; \varepsilon_{23L} \tag{118}$$

$$b_{31} = 0 \tag{119}$$

$$b_{32} = \frac{A_5 \; h''_2 \; h_3}{D_2} \tag{120}$$

$$b_{33} = -A_5 \left(h_3 + \frac{1}{R_B} - \frac{A_5 h_3^2}{D_2}\right) \tag{121}$$

$$c_3 = A_5 \left(\frac{T_a}{R_B} + \frac{\frac{h_3 2 G_2 C_P}{A_6} T_{in2}}{D_2}\right) \tag{122}$$

Collector Type III

Only three equations are required for collector type III. Heat balances on the absorber, the bottom and the air going through are writtten in Appendix B. The equations used to determine the film convection coefficients between the absorber and the bottom are those used for collector type II for channel 2. The emissivity factor is also calculated using equation (99).

Figure 15 shows the heat balances on this collector type. The final equations are shown below.

$$F_1(T_1, T_2) = a_{11}T_1^4 + a_{12}T_2^4 + b_{11}T_1 + b_{12}T_2 + c_1 = 0 \tag{123}$$

$$F_2(T_1, T_2) = a_{21}T_1^4 + a_{22}T_2^4 + b_{21}T_1 + b_{22}T_2 + c_2 = 0 \tag{124}$$

where

$$a_{11} = \sigma (\varepsilon_{1L} + \varepsilon_{12L}) \tag{125}$$

$$a_{12} = -\sigma \varepsilon_{12L} \tag{126}$$

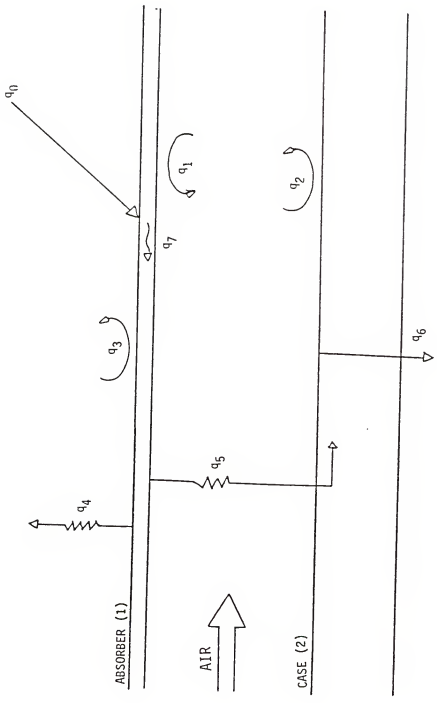


Figure 15. Schematic Diagram of Heat Balances on Collector Type III.

$$b_{11} = h_1 + h_w - \frac{h_1^2}{D} \tag{127}$$

$$b_{12} = -\frac{A_5 h_1 h_2}{D} \tag{128}$$

$$c_1 = -\alpha_{1S} q_0 - h_w T_a - \sigma \varepsilon_{1L} T_{sky}^4 - \frac{\frac{h_1 2 G C_p T_{in}}{A_6}}{D} \tag{129}$$

$$a_{21} = \sigma \varepsilon_{12L} \tag{130}$$

$$a_{22} = -\sigma \varepsilon_{12L} \tag{131}$$

$$b_{21} = \frac{A_5 h_1 h_2}{D} \tag{132}$$

$$b_{22} = -A_5 \left(h_2 + \frac{1}{R_B} - \frac{A_5 h_2^2}{D}\right) \tag{133}$$

$$c_2 = A_5 \left(\frac{\frac{2 G C_p h_2 T_{in}}{A_6}}{D} + \frac{T_a}{R_B}\right) \tag{134}$$

Drying Model

In order to calculate the average moisture content of the grain it is necessary to calculate some of the psychrometric properties of the air. The calculation of these properties is done using routines written by Chau (1986). The equations used in these routines come

from the psychrometric data adopted by the ASAE Standards since 1963 (ASAE Standards, 1986). The equations are in English units.

The determination of the average moisture content of the corn M(θ) can be solved by using the analytical solution proposed by Barre et al. (1971). This solution determines the moisture ratio MR(θ) and the temperature ratio with respect to time and depth. For the study of the solar drying system only the determination of themoisture ratio will be necessary. The depth used will always be the total depth of the stored grain.

$$MR = \frac{1}{D} \ln \frac{e^{D} + e^{\theta} - 1}{e^{\theta}} \qquad (133)$$

where

D = Characteristic depth factor, adimensional.

θ = time factor, adimensional.

The moisture ratio is related to the average moisture content with the following equation:

$$MR = \frac{M(\theta) - M_e}{M_0 - M_e}$$

where

M(θ) = average moisture content, dry basis, decimal.

M_o = initial moisture content, dry basis, decimal.

M_e = equilibrium moisture content, dry basis, decimal.

The depth factor is calculated using the following equation:

$$D = \frac{L\ K\ \rho_{corn}\ (M - M_e)}{G\ C_p\ (T_0 - T_e)}\ Y \tag{134}$$

and the time factor

$$\theta = K\ t \tag{135}$$

where

L = Latent heat of vaporization of corn at 15% moisture content, dry basis.

K = Drying constant, 1/h.

ρ_{corn} = Weight of dry matter per unit volume of grain.

G = Air mass flow rate, lb/h-ft^2.

C_p = Specific heat of the air.

T_0 = Air temperature at previous time.

T_e = Equilibrium air temperature.

Y = Grain depth.

The drying constant, K, has been defined by Barre et al. (1971) as a function of the saturation vapor pressure and the air velocity through the bin.

$$K = B\ P_s^M\ V^N \tag{136}$$

Several values have been suggested for the constants B, M and N. Sabbah et al. (1979) used the following values when simulating

shelled corn:

$$B = 6.272$$

$$M = 0.722$$

$$N = 0.8$$

P_s is given in Kg/cm^2 and V in m/s. The final equation used by Sabbah et al. is shown below.

$$K = 6.272\ P_s^{0.722}\ \left(\frac{V}{0.859}\right)^{0.8} \tag{137}$$

where 0.859 is the reference velocity in m/s.

The drying simulation is done within the routine called DRYING. This routine assumes the following variables constants:

ρ_{corn} = 606.86 Kg/m^3 (47.32 lb/Bu)

C_p = 1 KJ/Kg-C (0.24 Btu/lb-F)

ρ_{air} = 1.178 Kg/m^3 (0.0734 lb/ft^3)

L = 2918 KJ/Kg (1258 Btu/lb)

The latent heat of vaporization is considerably higher than the heat of vaporization of free water. The reason is that the grain exerts certain adhesive forces on the water which require more energy to release the water from the grain. Haynes (1961) presented values for the heat of vaporization of several materials at different moisture contents and temperatures. The value used in this model is

2926 KJ/Kg (1258 Btu/lb) which is for corn at 15 % moisture content (dry basis) and 38 C (100 F).

The equilibrium moisture content is calculated next by using the function EMC. The equation used in this model was derived by Henderson (1952) and then modified by Thompson (1967) to fit the data for corn.

$$1 - \frac{P_v}{P_s} = e^{(-3.8195E-05\ (T + 50)\ M_e^{\ 2})} \qquad (138)$$

where

M_e = Equilibrium moisture content.

Pv = Vapor pressure of grain.

Ps = Saturation vapor pressure.

T = absolute temperature of grain.

The equilibrium temperature is assumed to be the wet bulb temperature. This value is determined by calling the routine WBDBDP.

Economic Analysis

The end objective in simulating a solar drying system is to determine if the system is economically feasible. To fulfill this objective two calculations are made: the cost of drying one bushel of corn from a given initial moisture content to a final moisture content, and the determination of whether or not the solar collector is a good investment. The user should be aware of the assumptions and the basis on which the economic analysis has been made. To calculate

the cost of drying a bushel, the price of the fan, the heater, the solar collector and the energy used were taken into account. The cost of the energy used has been split into the energy used to force the air through the solar solar collector and through the corn, and the energy required to heat the air at night. Electric energy is assumed to be the input energy for the fan and LP gas for the heater. The total cost of the solar collector includes the initial cost of the materials, installation and the annual maintenance. The initial cost of materials as well as the installation cost are spread over the useful life of the respective material and these values added to the annual cost. The sum of these three factors is the equivalent annual cost of te solar collector. To determine whether the solar collector is a good investment or not the annual equivalent cost and the cost of energy required to drive the air through the solar collector are added and compared to the annual savings due to the solar energy collected. This energy is priced at the LP gas cost.

CHAPTER V
VALIDATION AND OBSERVATIONS

Drying Model

Since extensive use and validation of the logarithmic model has been done (Sabbha et al., 1979; Bakker-Arkema et al., 1974; etc.), a detailed validation is not necessary. However, a verification of this model was done by calculating the energy required to evaporate the water from the grain and comparing it to the energy given up by the air. This corresponds to the assumptions used in the development of the model. This energy, sensible heat, was calculated for each hour during a batch drying simulation.

$$\text{Energy} = G\, C_p\, (T_{in} - T_{out})$$

where

G = air mass flow rate going through grain.

C = specific heat of the air.

T_{in}, T_{out} = air temperatures.

The energy required to evaporate the water from the grain is calculated as follows:

$$\text{Energy}_{grain} = m_{grain}\, L_{water}\, (M.C._{initial} - M.C._{final})$$

where

m_{grain} = grain mass, dry matter.

L_{water} = heat of vaporization for corn at 15% M.C. (dry basis) and 100 F

M.C. = grain moisture content, dry basis.

Results of the calculations are shown on Table 3.

Table 3. Comparison of Energy Required to Dry the Corn and the Sensible Energy Given Up By the Air.

Airflow Rate m^3/h	Amount of Corn Kg	Initial M.C. %	Final M.C. %	Energy Grain KJ	Energy Air KJ	Relative Error %
1.89	26,886	25.00	17.59	5,813,509	5,818,536	0.09
2.36	26,886	25.00	17.49	5,891,965	5,897,401	0.09
2.83	26,886	28.21	17.52	8,386,831	8,366,794	0.24

The error on the total heat calculations is very small and can be attributed to round off errors. In any case such small errors would not affect the overall results of the model. During drying it is possible that the water vapor pressure in the air could be greater than the water vapor pressure of the grain, specially when it is raining. In this case moisture will be added to the corn. This was shown to be the case in some of the simulation results run with actual data for summer conditions in Florida.

Verification of the Collector Performance

The verification of the collector performance was done in two parts. The first part was to study the thermal efficiency as a function of the airflow rate and make a relative comparison of the efficiency of the three types of collectors. Engineering experience indicates that the highest efficiency should be obtained from the type II collector (air flows on both sides of absorber), the lowest from type III collector (bare plate collector) and type I (air flows above absorber) should be in between. Figure 16 shows the results given by the model. The second part of this verification was to analyze each collector type individually and check it with available data.

Collector Type I

Experimental data from Talbot and Elfino (no date a, b), from Chau and Baird (1980) and from Baird (1986), and simulated data from Parker (1981a) are used to compare simulated results from the developed model SOLDRY. Unfortunately, data are not complete; in all the cases wind velocity has not been reported and dimensions on the collectors and construction materials are not always reported. Data provided from Talbot and Elfino (no date a) are listed below:

Lewis Farm

Location: Ocala, Fl., at approximately 29 degrees latitude.

Collector Dimensions: Length = 30 m (100 ft)

Width = 5.45 m (18 ft)

Height = 1.5 m (5 ft), estimated

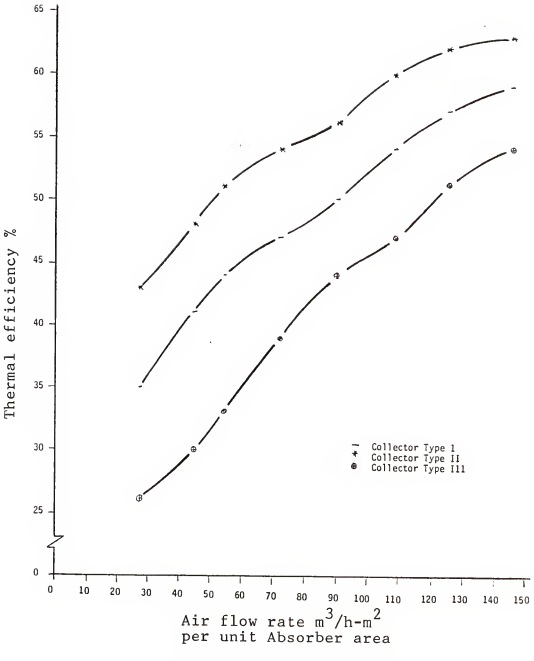


Figure 16. Collector Efficiencies as a Function of Airflow Rate Per Unit of Absorber Area.

Materials: Cover = Corrugated fiberglass

Absorber = Common black paint

Insulation = 1.25 cm (0.5 in.) styrofoam

Month in which the system was tested = October

Daily Total Horizontal Radiation (8 h) = 14,304 KJ/m^2

(1260 Btu/ft^2)

Daily Average Thermal Efficiency = 42%

Table 4 presents the simulated results from the model for type I collector.

Table 4. Simulated Results with SOLDRY for Collector Type I, Using Data from October 1985.

Airflow Rate per Unit Absorber Area $m^3/h\text{-}m^2$ (CFM/ft^2)	Daily Hor. Rad. KJ/m^2 (Btu/ft^2)	Thermal Efficiency %
5 (3)	13,780 (1,214)	32
5 (3)	14,475 (1,275)	30

Collector Type II

Experimental data were collected by Chau and Baird (1980) and a least square fitting curve was calculated for the thermal efficiency as a function of the airflow rate. They studied the influence of the total horizontal radiation over the thermal efficiency of the collector and found that it has a negligible effect. Figure 17 shows a curve from Chau and Baird (1980) and a curve showing average data

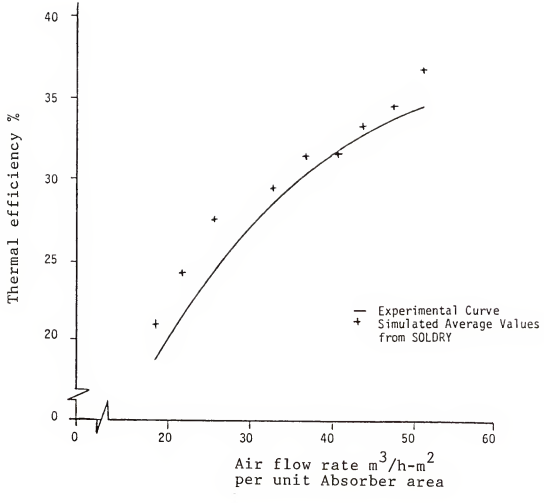


Figure 17. Comparison of Field Data with SOLDRY Model Simulation Results, Collector Type II.

from SOLDRY. Data provided by Chau and Baird for the experiments they ran are listed below:

Location: Gainesville, Fl.

Latitude 29.5

Longitude 82

Dimensions: Length = 30 m (96 ft)

Width = 3.6 m (12 ft)

Height = 20 cm (8 in.)

Materials: Cover = clear polyethylene

Absorber = black polypropylene screen with 45% openings and black polyethylene on the ground.

Insulation = urethane 3.17 cm (1.25 in.) thick

Time of Testing = June

Collector Type III

Data from Talbot and Elfino (no date b) are as follows:

Month: November

Total Daily Horizontal Radiation = 7,947 KJ/m^2 (700 Btu/ft^2)

Dimensions: Length = 18.16 m (60 ft)

Width = 12.11 m (40 ft)

Heigth = 10 cm (4 in.)

Airflow Rate = 30.47 $m^3/h\text{-}m^2$ (1.67 CFM/ft^2)

Thermal Efficiency = 12%

Simulated data with SOLDRY for this system are given in Table 5.

Table 5. Simulated Results with SOLDRY for Collector Type III, Using Data from Gainesville, FL, November 1985.

Airflow Rate per Unit Absorber Area $m^3/h\text{-}m^2$ (CFM/ft^2)	Total Daily Hor. Radiation KJ/m^2 (Btu/ft^2)	Thermal Efficiency %
30.47 (1.67)	8,136.29 (716.70)	31
30.47 (1.67)	8,768.63 (772.40)	24
773.10 (1.67)	8,776.58 (773.10)	19

Experimental data from Baird (1986) are as follows:

Month = August

Instantaneous Total Hor. Radiation = 0.69 KW/m^2 (220 $Btu/h\text{-}ft^2$)

Airflow Rate = 12.74 $m^3/h\text{-}m^2$ (7.5 CFM/ft^2)

Thermal Efficiency = 59.90 %

Table 6 gives the results using SOLDRY to simulate the previous conditions for several days with various wind speeds.

Table 6. Simulation Results with SOLDRY for Collector Type III, Using Data from Gainesville, FL, June 1985.

Horizontal Radiation $KJ/m^2\text{-}h$	Wind Speed m/s	Thermal Efficiency %
2281.71	2.50	54.80
2596.16	2.59	54.07
2705.13	1.74	59.55
2462.21	4.07	46.78
2516.69	1.52	61.00
2747.14	1.25	63.00
2412.26	1.52	61.18
2487.18	0.67	68.02

The results of the model SOLDRY compared with experimental and simulated values gives an overall acceptable result. The work done by Talbot and Elfino (no date a, b) was aimed to demonstrate the use of solar collectors in commercial farms and therefore the experimental data they took was rough. Tests presented by Chau and Baird (1980) and by Baird (1986) give very close results with simulation results using SOLDRY. Data reported by Parker (1981a) are incomplete and to compare it with results done with SOLDRY it was necessary to guess the input parameters. These are reported in Table 7. It is important though to see how different the performance of this type of collector is just by changing the cover material.

Table 7. Comparison of Simulation Results from Parker and SOLDRY for Collectors Types I, II and III.

	THERMAL EFFICIENCY %		
	Type I	Type II	Bare Plate
Parker	47.0	51.5	27.0
SOLDRY			28.0
a) Using Glass for Cover	49.0	59.0	
b) Using Polyethylene for Cover	28.0	34.0	

Although the SOLDRY model has been designed for a farmer or a county agent to determine the economic feasibility of a specific solar

collector with a specific airflow rate and materials, the model can also be used for engineers to determine design parameters on solar drying systems. As an example, an engineer can obtain the results of simulation for the three different types of collectors made with the same insulation and absorber materials (Table 8). The results (Table 8) have been extracted from the output files such as the one presented in Appendix E. Table 8 is presented as an example using specific conditions, and the results are not to be used as a general guide to choose among collectors since the economic feasibility is very dependent on the specific inputs. For the inputs used in Table 8 all solar collectors would be economically feasible if used for more than 36 days out of a year and for some collectors 18 days of use per year would result in a good investment. Even though the initial cost of a solar collector is high, it can be seen that the number of days of use required to be economically feasible is less than some of the low-cost systems. However, if a farmer is not sure about his future plans it might be wiser to invest less money on the system. The importance of such studies is to determine what would be most practical for each farmer.

Final Observations

The SOLDRY model takes into account materials for the simulation of the collector performance and for the economic analysis. Since the SOLDRY model is intended for nonscientists such as county extension agents, farmers and solar collector constructors, the outputs have

Table 8. Simulation Results Using SOLDRY for Comparing the Three Types of Collectors Using Two Different Cover Materials and At Four Different Airflow Rates.

Collector	Cover Material	Initial Cost $/100 m^2	Equivalent Annual Cost $	Airflow Rate per Unit of Absorber Area m^3/m^2-h (CFM/ft^2)		Daily Savings $	Minimum Use per Year to Be Economical Days
Type I	Polyethylene	596.88	180.98	45.71	(2.5)	5.36	34
Air flows above the absorber				54.85	(3.0)	4.97	36
				64.00	(3.5)	5.68	32
				91.42	(5.0)	6.80	27
	Corrugated fiberglass	896.88	235.13	45.71	(2.5)	7.83	30
				54.85	(3.0)	7.18	33
				64.00	(3.5)	7.49	31
				91.42	(5.0)	7.90	30
Type II	Polyethylene	596.88	180.98	45.71	(2.5)	5.46	33
Air flows above and below the absorber				54.85	(3.0)	6.27	29
				64.00	(3.5)	7.61	24
				91.42	(5.0)	8.57	21
	Corrugated fiberglass	896.88	235.13	45.71	(2.5)	8.52	28
				54.85	(3.0)	8.58	27
				64.00	(3.5)	8.73	27
				91.42	(5.0)	9.97	24
Type III		506.88	134.89	45.71	(2.5)	4.85	28
Bare plate Air flows below absorber				54.85	(3.0)	5.64	24
				64.00	(3.5)	6.16	22
				91.42	(5.0)	7.49	18

been designed as simple as possible yet complete so the user could check the data. The model, however, can be used by engineers to improve designs, optimize operating conditions select the best collector materials, etc. An additional file for output called TEMP.OUT prints the temperatures at the outlet of the collector for the cover, the absorber and the air coming out of the collector. Intermediate values such as solar angles, hourly efficiencies of the collector and temperature of the solar collector components are calculated throughout the air path. If a researcher is interested in these values it would be simple to create new files and output the values of interest.

A major effort has been done to document the model. A list of variables and an explanation of each routine has been written (see appendices G and H). Also the source code has been outlined so a person could follow it.

The fixed costs of the solar drying system (the solar collector) is the major cost, and the economic feasibility depends on how often the solar collector is used. Usually, in Florida, a farmer has the opportunity to grow several crops within a year. The simulation model, SOLDRY, can simulate only the drying of corn. However, it should be easy to change the model to accommodate other crops. In fact, a satisfactory economic estimate could be obtained by using the corn drying model for crops such as soybeans, peanuts, and small grains.

Further work should include the writing of a computer program to optimize certain parameters such as materials, collector size, air

flow rate, etc. This normally means minimizing the cost of drying within the constraints provided by the farmer. The constraints migh include maximum initial investment, maximum time allowed for drying, time available for management, capacity of existing equipment, etc. The present model, a satisfactory model for selecting the best solar drying system would be to determine the constraints that the farmer wants to place on the system and then run the model using a variety of inputs until acceptable design and operating conditions are obtained. Also a sensitivity analysis could be run on each variable in order to determine which are the most critical.

CHAPTER VI
CONCLUSIONS

1) An engineering/economic analysis has been developed for typical solar drying systems. It includes the simulation of the solar collector performance and grain drying, and performs an economic analysis of the system.

2) Results of the validation of the collector performance for the three types of collectors are generally in good agreement with experimental data and other mathematical models.

3) The input and output information are simple so that a non scientist can use the model to determine the feasibility of solar drying systems.

4) The simulation of the solar drying system is complete and well documented allowing engineers to improve designs and optimize the operating conditions.

5) Simulations have shown that the cover material is very important for the collector performance. In one case the thermal performance of the collector was reduced by 42% for a covered plate collector when a plastic transparent cover was used instead of glass.

6) Another important factor, usually neglected by most researchers, is the wind velocity. One simulation showed 36% thermal efficiency reduction on a bare plate collector when wind speed increased from 0.67 to 4.07 m/s.

7) For the sample simulations presented in this thesis, solar drying systems were economically feasible for a minimum use per year ranging from 18 days for a bare plate collector to 36 days for a polyethylene covered plate collector.

APPENDIX A
DEVELOPMENT OF EQUATIONS
FOR COLLECTOR TYPE II

Heat balance on cover.

$$q_1 + q_5 + q_{12} = q_8 + q_9 + q_{13} \quad \text{(A-1)}$$

Heat balance on absorber.

$$q_4 + q_6 = q_7 + q_{10} + q_{12} + q_{14} + q_{15} \quad \text{(A-2)}$$

Heat balance on the bottom.

$$q_{15} = q_{11} + q_{16} \quad \text{(A-3)}$$

Heat balance on Fluid 1 and 2 (see figure 18).

$$G_1 C_p (T_{out1} - T_{in1}) = q_8 + q_7 \quad \text{(A-4)}$$

$$G_2 C_p (T_{out2} - T_{in2}) = q_{10} + q_{11} \quad \text{(A-5)}$$

G1 and G2 are the air mass flow rates going through the respective channel.

Notation: A_1 = Cover area

A_2 = Absorber area

A_3 = Bottom area

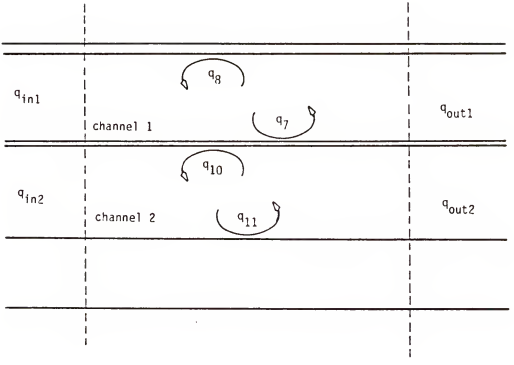


Figure 18. Heat Balances on Air Flowing Through Channels 1 and 2 on Collector Type II.

N_0 = Number of segments in which the collector has been divided for its simulation.

$$A_4 = \frac{A_1}{A_2}$$

$$A_5 = \frac{A_3}{A_2}$$

$$A_6 = \frac{A_2}{N_0}$$

q_0 = Total incident radiation (direct and diffuse) incident on cover, Btu/ft^2.

$\tau_{1S} q_0$ = Energy transmitted through cover, total, Btu/ft^{2}hr.

ε_{12L} = Emissivity factor for parallel plates between 1 and 2

ε_{23L} = Emissivity factor for parallel plates between 2 and 3

$$\rho_{12S} = \frac{\rho_{2S}}{(1 - \rho_{1S}\ \rho_{2S})} \qquad \text{(A-6)}$$

$$q_1 = A_4\ \alpha_{1S}\ q_0 \qquad \text{(A-7)}$$

$$q_4 = \alpha_{2S}\tau_{1S} q_0 \qquad \text{(A-8)}$$

$$q_5 = A_4\ \alpha_{1S}\ \rho_{12S}\ q_0 \qquad \text{(A-9)}$$

$$q_6 = \alpha_{2S}\ \rho_{1S}\ \rho_{12S}\ \tau_{1S}\ q_0 \tag{A-10}$$

$$q_7 = h'_2\ (T_2 - T_{f1}) \tag{A-11}$$

$$q_8 = A_4\ h_1\ (T_1 - T_{f1}) \tag{A-12}$$

$$q_9 = A_4\ h_w\ (T_1 - T_a) \tag{A-13}$$

$$q_{10} = h''_2\ (T_2 - T_{f2}) \tag{A-14}$$

$$q_{11} = A_5\ h_3\ (T_3 - T_{f2}) \tag{A-15}$$

$$q_{12} = \sigma\ \varepsilon_{23L}\ (T_2^4 - T_1^4) \tag{A-16}$$

$$q_{13} = A_4\ \sigma\ \varepsilon_{1L}\ (T_1^4 - T_{sky}^4) \tag{A-17}$$

$$q_{14} = \sigma\ \tau_{1L}\ \varepsilon_{2L}(T_{2L}^4 - T_{sky}^4) \tag{A-18}$$

$$q_{15} = \sigma\ \varepsilon_{23L}\ (T_2^4 - T_3^4) \tag{A-19}$$

$$q_{16} = \frac{A_4}{R_B}\ (T_3 - T_a) \tag{A-20}$$

The airmass flow rate G1 and G2 are found as follows:

Given airflow rate, CFM, cross section area of collector, cross section shape of absorber (triangular or flat plate), shape and height of absorber from the bottom (for triangular shape maximum height); the

model calculates the cross section area between bottom and absorber A_{C2}. Area of the other channel would be $A_{C1} = A_{cross} - A_{C2}$.

$$G = CFM \times 60 \times \rho_{air} \tag{A-21}$$

$$G_1 = G \times \frac{A_1}{A_{cross}} \tag{A-22}$$

$$G_2 = G - G_1 \tag{A-23}$$

where

A_{cross} = total cross sectional area of collector.

A_{C1} = cross sectional area, channel 1.

A_{C2} = cross sectional area, channel 2.

ρ_{air} = air density.

G = total air mass flow rate.

G_1 = air mass flow rate through channel 1.

G_2 = air mass flow rate through channel 2.

CFM = airflow rate.

Heat balance on fluid 1 using expressions:

$$G_1 C_p (T_{out1} - T_{in1}) = A_6 (h'_2 (T_2 - T_{f1}) + A_4 h_1 (T_1 - T_{f1})) \tag{A-24}$$

where $T_{f1} = \frac{T_{in1} + T_{out1}}{2}$ (A-25)

or

$$T_{out1} = 2T_{f1} - T_{in1} \tag{A-26}$$

$$\frac{2G_1C_p}{A_6}(T_{f1} - T_{in1}) = h_2'(T_2 - T_{f1}) + A_4 h_1 (T_1 - T_{f1}) \tag{A-27}$$

Solving for T_{f1}:

$$T_{f1} = \frac{\frac{2 G_1 C_P}{A_6} T_{in1} + h_2' T_2 + A_4 h_1 T_1}{D_1} \tag{A-28}$$

where

$$D_1 = \frac{2 G_1 C_P}{A_6} + h_2' + A_4 h_1 \tag{A-29}$$

Heat balance on fluid 2 using expressions

$$G_2C_p (T_{out2} - T_{in2}) =$$

$$A_6 \left(h_2'' (T_2 - T_{f2}) + A_5 h_3 (T_3 - T_{f2})\right) \tag{A-30}$$

where

$$T_{f2} = \frac{T_{out2} + T_{in2}}{2} \tag{A-31}$$

or

$$T_{out2} = 2T_{f2} - T_{in2} \tag{A-32}$$

$$\frac{2G_2C_P}{A_6}\left(T_{f2} - T_{in2}\right) =$$

$$h_2'' (T_2 - T_{f2}) + A_5\, h_3 (T_3 - T_{f2}) \tag{A-33}$$

Solving for T_{f2}

$$T_{f2} = \frac{\frac{2\,G_2\,C_P}{A_6} T_{in2} + h_2''\, T_2 + A_5\, h_3\, T_3}{D_2} \tag{A-34}$$

where

$$D_2 = \frac{2\,G_2\,C_P}{A_6} + h_2'' + A_5\, h_3 \tag{A-35}$$

Heat balance on cover using expressions

$$q_1 + q_5 + q_{12} = q_8 + q_9 + q_{13}$$

$$A_4\, \alpha_{1S}\, q_0 + A_4\, \alpha_{1S}\, \rho_{12S}\, \tau_{1S}\, q_0 + \varepsilon_{12L}\, (T_2^4 - T_1^4)$$

$$= A_4\, h_1\, (T_1 - T_{f1}) + A_4\, h_w\, (T_1 - T_a) + \sigma\, A_4\, \varepsilon_{1L}\, (T_1^4 - T_{sky}^4) \tag{A-36}$$

Rearranging

$$(\sigma A_4 \varepsilon_{1L} + \sigma \varepsilon_{12L}) T_1^4 - \sigma \varepsilon_{12L} T_2^4$$

$$+ (A_4 h_1 + A_4 h_w) T_1$$

$$- A_4 \alpha_{1S}(q_0 + \rho_{12S} \tau_{1S} q_0) - A_4 h_w T_a$$

$$- \sigma A_4 \varepsilon_{1L} T_{sky}^4 - A_4 h_1 T_{f1} = 0 \qquad \text{(A-37)}$$

Replacing T_{f1} by equation (A-30) and rearranging.

$$\sigma (A_4 \varepsilon_{1L} + \varepsilon_{12L}) T_1^4 - \sigma \varepsilon_{12L} T_2^4$$

$$+ A_4 \left[h_1 + h_w - \frac{A_4 h_1^2}{D_1}\right] T_1 - A_4 \frac{h_1 h_2'}{D_1} T_2$$

$$- A_4 \left[\alpha_{1S}(q_0 + \rho_{12S} \tau_{1S} q_0) + h_w T_a + \sigma \varepsilon_{1L} T_{sky}^4 + h_1 \frac{2 G_1 C_p T_{in1}}{D_1}\right] = 0$$

(A-38)

Heat balance on absorber using expressions.

$$q_4 + q_6 = q_7 + q_{10} + q_{12} + q_{14} + q_{15}$$

$$\alpha_{2S} \tau_{1S} q_0 + \alpha_{2S} \rho_{1S} \rho_{12S} \tau_{1S} q_0 =$$

$$h_2' (T_2 - T_{f1}) + h_2'' (T_2 - T_{f2}) + \sigma \varepsilon_{12L} (T_2^4 - T_1^4)$$

$$+ \sigma \tau_{1L} \varepsilon_{2L} (T_2^4 - T_{sky}^4) + \sigma \varepsilon_{23L} (T_2^4 - T_3^4) \qquad \text{(A-39)}$$

Rearranging.

$$\sigma \varepsilon_{12L} T_1^4 - \sigma (\varepsilon_{12L} + \varepsilon_{23L} + \tau_{1L}\varepsilon_{2L}) T_2^4$$

$$+ \sigma \varepsilon_{23L} T_3^4 - (h_2' + h_2'') T_2$$

$$+ \alpha_{2S} \tau_{1S} q_0 (1 + \rho_{1S} \rho_{12S}) + \sigma \tau_{1L}\varepsilon_{2L} T_{sky}^4$$

$$+ h_2' T_{f1} + h_2'' T_{f2} = 0 \qquad \text{(A-40)}$$

Replacing T_{f1} and T_{f2} by equation (A-30) and (A-36), and rearranging.

$$\sigma \varepsilon_{12L} T_1^4 - \sigma (\varepsilon_{12L} + \varepsilon_{23L} + \tau_{1L}\varepsilon_{2L}) T_2^4$$

$$+ \sigma \varepsilon_{23L} T_3^4 + \frac{A_4 h_1 h_2'}{D_1} T_1$$

$$- (h_2' + h_2'' - \frac{h_2'^2}{D_1} - \frac{h_2''^2}{D_2}) T_2 + \frac{A_5 h_2'' h_3}{D_2} T_3$$

$$+ \alpha_{2S} \tau_{1S} q_0 (1 + \rho_{1S} \rho_{12S}) + \sigma \tau_{1L} \varepsilon_{2L} T_{sky}^4$$

$$+ \frac{(h_2' 2G_1 C_P T_{in1})/ A_6}{D_1} + \frac{(h_2'' 2G_2 C_P T_{in2})/ A_6}{D_2} = 0 \qquad \text{(A-41)}$$

Heat balance on the bottom using expressions.

$$q_{15} = q_{11} + q_{16}$$

$$\sigma\ \varepsilon_{23L}\ (T_2^4 - T_3^4) = A_5\ h_3(T_3 - T_{f2}) + \frac{A_5}{R_B}\ (T_3 - T_a) \qquad \text{(A-42)}$$

Rearranging

$$\sigma\ \varepsilon_{23L}\ T_2^4 - \sigma\ \varepsilon_{23L}\ T_3^4 - A_5\ (h_3 + \frac{1}{R_B})$$

$$+\ \frac{A_5}{R_B}\ T_a + A_5\ h_3\ T_{f2} = 0 \qquad \text{(A-43)}$$

Replacing T_{f2} by equation (A-36) and rearranging.

$$\sigma\ \varepsilon_{23L}\ T_2^4 - \sigma\ \varepsilon_{23L}\ T_3^4 + \frac{A_5\ h_2'' h_3}{D_2}\ T_2$$

$$- A_5\ (h_3 + \frac{1}{R_B} - \frac{A_5\ h_3^2}{D_2})T_3$$

$$+ A_5\ (\frac{1}{R_B}\ T_a + \frac{h_3(\frac{2\ G\ C_p}{A_6})\ T_{in2}}{D_2}) = 0 \qquad \text{(A-44)}$$

Equations (A-40), (A-43) and (A-46) can be written as follows:

$$F_1(T_1, T_2, T_3) = a_{11}T_1^4 + a_{12}T_2^4 + a_{13}T_3^4 + b_{11}T_1 + b_{12}T_2 + b_{13}T_3 + c_1 = 0 \qquad \text{(A-45)}$$

$$F_2(T_1, T_2, T_3) = a_{21}T_1^4 + a_{22}T_2^4 + a_{23}T_3^4 + b_{21}T_1 + b_{22}T_2 + b_{23}T_3 + c_2 = 0 \qquad \text{(A-46)}$$

$$F_3(T_1, T_2, T_3) = a_{31}T_1^4 + a_{32}T_2^4 + a_{33}T_3^4 + b_{31}T_1 + b_{32}T_2 + b_{33}T_3 + c_3 = 0 \qquad \text{(A-47)}$$

where

$$a_{11} = \sigma (A_4 \varepsilon_{1L} + \varepsilon_{12L}) \tag{A-48}$$

$$a_{12} = -\sigma \varepsilon_{12L} \tag{A-49}$$

$$a_{13} = 0 \tag{A-50}$$

$$b_{11} = A_4 \left(h_1 + h_w - \frac{A_4 h_1^2}{D_1}\right) \tag{A-51}$$

$$b_{12} = -A_4 \frac{h_1 h_2'}{D_1} \tag{A-52}$$

$$b_{13} = 0 \tag{A-53}$$

$$c_1 = -A_4 \left(\alpha_{1S} (q_0 + \rho_{12S} \tau_{1S} q_0) + h_w T_a + \sigma \varepsilon_{1L} T_{sky}^4 + h_1 \frac{2 G_1 C_P T_{in1}}{D_1}\right) \tag{A-54}$$

$$a_{21} = \sigma \varepsilon_{12L} \tag{A-55}$$

$$a_{22} = -\sigma (\varepsilon_{12L} + \varepsilon_{23L} + \tau_{1L} \varepsilon_{2L}) \tag{A-56}$$

$$a_{23} = \sigma \varepsilon_{23L} \tag{A-57}$$

$$b_{21} = \frac{A_4 h_1 h_2'}{D_1} \tag{A-58}$$

$$b_{22} = -\left(h_2' + h_2'' - \frac{h_2'^2}{D_1} - \frac{h_2''^2}{D_2}\right) \tag{A-59}$$

$$b_{23} = \frac{A_5 h_2'' h_3}{D_2} \tag{A-60}$$

$$c_2 = \alpha_{2S}\,\tau_{1S}\,q_0\,(1 + \rho_{1S}\,\rho_{12S}) + \sigma\,\tau_{1L}\varepsilon_2 T_{sky}^4 + \frac{\dfrac{h_2'\,2\,G_1\,C_P\,T_{in1}}{A_6}}{D_1} + \frac{\dfrac{h_2''\,2\,G_2\,C_P\,T_{in2}}{A_6}}{D_2} \qquad \text{(A-61)}$$

$$a_{31} = 0 \qquad \text{(A-62)}$$

$$a_{32} = \sigma\,\varepsilon_{23L} \qquad \text{(A-63)}$$

$$a_{33} = -\sigma\,\varepsilon_{23L} \qquad \text{(A-64)}$$

$$b_{31} = 0 \qquad \text{(A-65)}$$

$$b_{32} = \frac{A_5\,h_2''\,h_3}{D_2} \qquad \text{(A-66)}$$

$$b_{33} = -A_5\left(h_3 + \frac{1}{R_B} - \frac{A_5\,h_3^2}{D_2}\right) \qquad \text{(A-67)}$$

$$c_3 = A_5\left(\frac{T_a}{R_B} + \frac{\dfrac{h_3\,2\,G_2\,C_P}{A_6}\,T_{in2}}{D_2}\right) \qquad \text{(A-68)}$$

APPENDIX B
DEVELOPMENT OF EQUATIONS
FOR COLLECTOR TYPE III

Heat balance on absorber.

$$q_7 = q_1 + q_3 + q_4 + q_5 \tag{B-1}$$

Heat balance on the bottom.

$$q_5 = q_2 + q_6 \tag{B-2}$$

Notation:

A_1 = absorber area.

A_2 = bottom area.

N_0 = number of segments in which the collector is divided.

$$A_5 = \frac{A_2}{A_1}$$

$$A_6 = \frac{A_1}{N_0}$$

q_0 = total incident radiation.

ε_{12L} = emissivity factor between absorber and bottom.

$$\varepsilon_{12L} = \frac{1}{\frac{1}{\varepsilon_{1L}} + \frac{1}{\varepsilon_{2L}} - 1} \tag{B-3}$$

$$q_1 = h_1 (T_1 - T_f) \tag{B-4}$$

$$q_2 = A_5 h_2 (T_2 - T_f) \tag{B-5}$$

$$q_3 = h_w (T_1 - T_a) \tag{B-6}$$

$$q_4 = \sigma \varepsilon_{1L} (T_1^4 - T_{sky}^4) \tag{B-7}$$

$$q_5 = \sigma \varepsilon_{12L} (T_1^4 - T_2^4) \tag{B-8}$$

$$q_6 = \frac{A_5}{R_B} (T_2 - T_a) \tag{B-9}$$

$$q_7 = \alpha_{1S} q_0 \tag{B-10}$$

Energy balance on fluid (see figure 19).

$$q_{out} - q_{in} = q_1 + q_2 \tag{B-11}$$

$$G C_P (T_{out} - T_{in}) = A_6 \left(h_1 (T_1 - T_f) + A_5 h_2 (T_2 - T_f)\right) \tag{B-12}$$

Assume

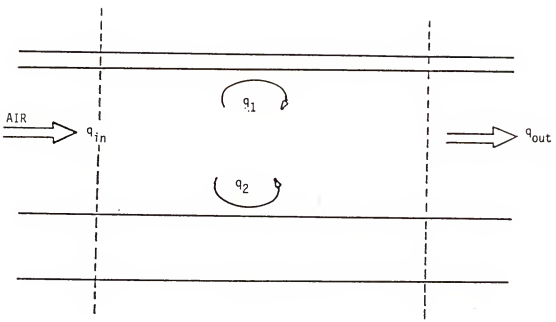


Figure 19. Heat Balance on Air Channel on Collector Type III.

$$T_f = \frac{T_{out} + T_{in}}{2} \tag{B-13}$$

then

$$T_{out} = 2\,T_f - T_{in} \tag{B-14}$$

Using equations (B-12) and (B-14).

$$\frac{2\,G\,C_p}{A_6}\,(T_f - T_{in}) = h_1\,(T_1 - T_f) + A_5\,h_2\,(T_2 - T_f) \tag{B-15}$$

$$T_f = \frac{\frac{2\,G\,C_p}{A_6}\,T_{in} + h_1\,T_1 + A_5\,h_2\,T_2}{D} \tag{B-16}$$

where

$$D = \frac{2\,G\,C_p}{A_6} + h_1 + A_5\,h_2 \tag{B-17}$$

Heat balance on absorber using expressions.

$$q_7 = q_1 + q_3 + q_4 + q_5$$

$$\alpha_{1S}\,q_0 = h_1(T_1 - T_f) + h_w(T_1 - T_a)$$

$$+ \sigma\,\epsilon_{1L}\,(T_1^4 - T_{sky}^4) + \sigma\,\epsilon_{12L}\,(T_1^4 - T_2^4) \tag{B-18}$$

Rearranging

$$\sigma (\varepsilon_{1L} + \varepsilon_{12L}) T_1^4 - \sigma \varepsilon_{12L} T_2^4 + (h_1 + h_w) T_1$$

$$- \alpha_{1S} q_0 - \sigma \varepsilon_{1L} T_{sky}^4 - h_w T_a - h_1 T_f = 0 \qquad \text{(B-19)}$$

Replacing T_f by equation (B-16) and rearranging.

$$\sigma (\varepsilon_{1L} + \varepsilon_{12L}) T_1^4 - \sigma \varepsilon_{12L} T_2^4 + \left(h_1 + h_w - \frac{h_1^2}{D}\right) T_1$$

$$- \frac{A_5 h_1 h_2 T_2}{D} - \alpha_{1S} q_0 - h_w T_a$$

$$- \sigma \varepsilon_{1L} T_{sky}^4 - \frac{\frac{h_1 2 G C_p}{A_6} T_{in}}{D} = 0 \qquad \text{(B-20)}$$

Heat balance on the bottom using expressions.

$$q_5 = q_2 + q_6$$

$$\sigma \varepsilon_{12L} (T_1^4 - T_2^4) = A_5 h_2 (T_2 - T_f) + \frac{A_5}{R_B} (T_2 - T_a) \qquad \text{(B-21)}$$

Rearranging

$$\sigma \varepsilon_{12L} T_1^4 - \sigma \varepsilon_{12L} T_2^4 - A_5 \left(h_2 + \frac{1}{R_B}\right) T_2$$

$$+ \frac{A_5}{R_B} T_a + A_5 h_2 T_f = 0 \qquad \text{(B-22)}$$

Replacing T_f by equation (B-16) and rearranging.

$$\sigma \varepsilon_{12L} T_1^4 - \sigma \varepsilon_{12L} T_2^4 + \frac{A_5 h_1 h_2}{D} T_1$$

$$- A_5 \left(h_2 + \frac{1}{R_B} - \frac{A_5 h_2^2}{D}\right) T_2$$

$$+ \frac{A_5}{R_B} T_a + \frac{A_5 h_2 \dfrac{2 G C_P}{A_6}}{D} T_{in} = 0 \qquad \text{(B-23)}$$

Equations (B-21) and (B-24) can be written as follows.

$$F_1(T_1, T_2) = a_{11} T_1^4 + a_{12} T_2^4 + b_{11} T_1 + b_{12} T_2 + c_1 = 0 \qquad \text{(B-24)}$$

$$F_2(T_1, T_2) = a_{21} T_1^4 + a_{22} T_2^4 + b_{21} T_1 + b_{22} T_2 + c_2 = 0 \qquad \text{(B-25)}$$

where

$$a_{11} = \sigma (\varepsilon_{1L} + \varepsilon_{12L}) \qquad \text{(B-26)}$$

$$a_{12} = - \sigma \varepsilon_{12L} \qquad \text{(B-27)}$$

$$b_{11} = h_1 + h_w - \frac{h_1^2}{D} \qquad \text{(B-28)}$$

$$b_{12} = - \frac{A_5 h_1 h_2}{D} \qquad \text{(B-29)}$$

$$c_1 = -\alpha_{1S} q_0 - h_w T_a - \sigma \varepsilon_{1L} T_{sky}^4 - \frac{\frac{h_1 \, 2 \, G \, C_p \, T_{in}}{A_6}}{D} \qquad \text{(B-30)}$$

$$a_{21} = \sigma \varepsilon_{12L} \qquad \text{(B-31)}$$

$$a_{22} = -\sigma \varepsilon_{12L} \qquad \text{(B-32)}$$

$$b_{21} = \frac{A_5 h_1 h_2}{D} \qquad \text{(B-33)}$$

$$b_{22} = -A_5 \left(h_2 + \frac{1}{R_B} - \frac{A_5 h_2^2}{D}\right) \qquad \text{(B-34)}$$

$$c_2 = A_5 \left(\frac{\frac{2 \, G \, C_p \, h_2 \, T_{in}}{A_6}}{D} + \frac{T_a}{R_B}\right) \qquad \text{(B-35)}$$

APPENDIX C
EQUATIONS TO CALCULATE TRANSMISSION THROUGH THE COVER

The transmissivity of solar radiation as a function of the angle of incidence is presented by Godbey et al. (1977). The data presented by Godbey are shown below. These data were used along with the Least Square method to fit the equations used in the model. Equations for the different materials are of third and fourth order. The order of these equations depends on whether the standard error is greater than 2.5 or not. When the standard error was greater then a fourth order equation was used.

Ref. No.	COVER MATERIAL	SOLAR ENERGY TRANSMISSION, % Angle of incidence, degrees. 0	14	30	45	60	67
1	Polyethylene, 4-mil (0.10 mm) UV resistant	92	91	88	86	82	67
2	Flat fiber glass Regular, 25-mil (0.64 mm)	87	84	82	80	73	57
3	Flat fiber glass Premium, 40-mil (1.02 mm)	77	78	75	65	46	33
4	Corrugated fiber glass 40-mil (1.02 mm)	81	80	78	75	64	43
5	Glass double strength 1/8-in (3.18 mm)	89	89	88	85	82	74

Curve for reference No. 1 polyethylene, 4-mil:

$$F(X) = 91.87642 + 0.5968210\ X - 6.773251E\text{-}02\ X^2 + 1.904472E\text{-}03\ X^3 - 1.653285E\text{-}05\ X^4$$

Standard error = 2.162

Correlation coefficient = 0.994

Curve for reference No. 2 flat fiber glass, regular:

$$F(X) = 86.89533 + 0.1741256\ X - 4.129718E\text{-}02\ X^2 + 1.359614E\text{-}03\ X^3 - 1.313645E\text{-}05\ X^4$$

Standard error = 1.851

Correlation coefficient = 0.997

Curve for reference No. 3 flat fiber glass, premium:

$$F(X) = 76.99157 + 0.1462668\ X - 0.0032922\ X^2 - 1.295998E\text{-}04\ X^3$$

Standard error = 0.112

Correlation coefficient = 1.

Curve for reference No.4 corrugated fiber glass

$$F(X) = 80.88613 + 0.4924977\ X - 5.83847E\text{-}02\ X^2 - 1.751727E\text{-}03\ X^3 - 1.663578E\text{-}05\ X^4$$

Standard error = 2.009

Correlation coefficient = 0.998

Curve for reference No.5 glass, double strength:

$$F(X) = 89.25328 - 0.1365373X + 6.896083E\text{-}03X^2 - 1.197128E\text{-}04X^3$$

Standard error = 1.850

Correlation coefficient = 0.98

APPENDIX D
NEWTON-RAPHSON METHOD FOR A SYSTEM
OF NONLINEAR EQUATIONS

The Newton-Raphson method is usually derived from the Taylor series expanded around a nearby point which is the previous guess. For a system of equations of n unknowns

$$f_1(\underline{X}^{i+1}) = 0 = f_1(\underline{X}^i) + \frac{\partial f_1(\underline{X}^i)}{\partial x_1} \frac{\delta_1^i}{1!} + \frac{\partial f_2^i(\underline{X})}{\partial x_2} \frac{\delta_2^i}{1!} + \cdots$$

$$+ \frac{\partial f_1(\underline{X}^i)}{\partial x_n} \frac{\delta_n^i}{1!} + O(h^2)$$

$$f_2(\underline{X}^{i+1}) = 0 = f_2(\underline{X}^i) + \frac{\partial f_2(\underline{X}^i)}{\partial x_1} \frac{\delta_1^i}{1!} + \frac{\partial f_2(\underline{X}^i)}{\partial x_2} \frac{\delta_2^i}{1!} + \cdots$$

$$+ \frac{\partial f_2(\underline{X}^i)}{\partial x_n} \frac{\delta_n^i}{1!} + O(h^2)$$

.
.
.

$$f_n(\underline{X}^{i+1}) = 0 = f_n(\underline{X}^i) + \frac{\partial f_n(\underline{X}^i)}{\partial x_1} \frac{\delta_1^i}{1!} + \frac{\partial f_n(\underline{X}^i)}{\partial x_2} \frac{\delta_2^i}{1!} + \cdots$$

$$+ \frac{\partial f_n(\underline{X}^i)}{\partial x_n} \frac{\delta_n^i}{1!} + O(h^2)$$

where $\underline{X}$ is the vector $[x_1, x_2, \ldots, x_n]^T$

$$\delta_1^i = (x_1^{i+1} - x_2^i)$$

$$\delta_2^i = (x_2^{i+1} + x_2^i)$$

$$\vdots$$

$$\delta_n^i = (x_n^{i+1} - x_n^i)$$

Using matrix notation

$$\underline{\delta}_i = [(x_1^{i+1} - x_1^i), (x_2^{i+1} - x_2^i), \ldots, (x_n^{i+1} - x_n^i)]^T$$

$$\underline{F}_i = [\, f_1(\underline{X}^i), f_2(\underline{X}^i), \ldots, f_n(\underline{X}^i)]^T$$

$$J^i = \begin{matrix} \frac{\partial f_1(\underline{X}^i)}{\partial x_1} & \frac{\partial f_1(\underline{X}^i)}{\partial x_2} & \cdots & \frac{\partial f_n(\underline{X}^i)}{\partial x_n} \\ \frac{\partial f_2(\underline{X}^i)}{\partial x_1} & \frac{\partial f_2(\underline{X}^i)}{\partial x_2} & \cdots & \frac{\partial f_2(\underline{X}^i)}{\partial x_n} \\ \vdots & & & \vdots \\ \frac{\partial f_n(\underline{X}^i)}{\partial x_1} & \frac{\partial f_n(\underline{X}^i)}{\partial x_2} & \cdots & \frac{\partial f_n(\underline{X}^i)}{\partial x_n} \end{matrix}$$

The matrix J^i is called the ith Jacobian matrix. The Taylor expansion can be written as follows.

$$0 = \underline{F}^i + J^i \underline{\delta}^i$$

or

$$J^i \underline{\delta}^i = - \underline{F}^i$$

This last equation is a system of linear equations in which the unknowns are the elements of δ^i. The roots are found when each element of δ^i is less than a maximum error allowed (ε), i.e., for a system of three equations:

$$\| x_1^{i+1} - x_1^i \| \leq \varepsilon$$

$$\| x_2^{i+1} - x_2^i \| \leq \varepsilon$$

$$\| x_3^{i+1} - x_3^i \| \leq \varepsilon$$

If any of these elements is larger than ε, then

$$x_1^{i+1} = x_1^i + \delta_1^i$$

$$x_2^{i+1} = x_1^i + \delta_2^i$$

$$x_3^{i+1} = x_3^i + \delta_3^i$$

and the elements of $\underline{F}$ and J calculated for the new vector

$$\underline{X} = [x_1^{i+1} \quad x_2^{i+1} \quad x_3^{i+1}]^T$$

This process is repeated until the roots are found. More information about this method can be found in Carnahan et al. (1969) and Rice (1983).

APPENDIX E
SCREENS FOR SELECTION OF COLLECTOR MATERIALS

REF. NO.	COVER MATERIAL	COST $/SQR.FT. INITIAL	INSTALLATION	ANNUAL MAINTENANCE	USEFUL LIFE YRS.	TRANSMISSIVITY % LONG WAVE	AVG. SHORT WAVE	FUNCT	EMIS %
1	POLYETHYLENE,4-MIL UV RESISTANT	0.06	0.02	0.01	2	80.0	88.8	POLYET	5.0
2	FLAT FIBER GLASS REGULAR,25-MIL	1.12	0.05	0.01	5	12.0	83.1	RFGLAS	5.0
3	FLAT FIBER GLASS PREMIUM,40-MIL	1.34	0.05	0.01	5	6.0	72.9	PFGLAS	5.0
4	CORRUGATED FIBER GLASS,40-MIL	0.35	0.03	0.01	5	8.0	79.2	CFGLS1	5.0
5	GLASS, DOUBLE STRENGTH 1/8-IN	2.00	0.15	0.01	10	3.0	87.8	GLASS	5.0

TYPE "0" IF YOU WANT TO SEE THE BEGINNING OF THE TABLE.
TYPE THE REFERENCE NUMBER OF THE MATERIAL YOU WANT ON YOUR COLLECTOR. (IF YOU HAVE ALREADY MADE YOUR CHOICE.)
TYPE ANY OTHER KEY IF YOU WANT TO SEE THE NEXT PAGE.

REF. No.	INSULATION MATERIAL	THICKNESS IN.	COSTS $/SQR. FT. INITIAL	INSTALLATION	ANNUAL MAINTENANCE	USEFUL LIFE YRS.	THERMAL(*) RESISTANCE PER INCH	PER THICKNESS
1	THERMOPLY	.75	.35	.02	.01	5	4.17	3.13
2	THERMOPLY	1.0	.47	.02	.01	5	4.17	4.17
3	THERMOPLY	1.5	.70	.02	.01	5	4.17	6.25
4	FIBER GLASS	3.5	.21	.02	.01	5	3.14	11.00
5	STYROFOAM	.50	.09	.02	.01	5	3.12	1.56
6	STYROFOAM	.75	.14	.02	.01	5	3.12	2.08
7	STYROFOAM	1.0	.20	.02	.01	5	3.12	3.12
8	STYROFOAM	1.5	.31	.02	.01	5	3.12	4.68
9	NO INSULATION	0.0	.01	.01	.00	5	0.00	----

* : THERMAL RESISTANCE IS LISTED IN (ft-h-F)/(Btu/THICKNESS LISTED).

TYPE "0" IF YOU WANT TO SEE THE BEGINNING OF THE TABLE.
TYPE THE REFERENCE NUMBER OF THE MATERIAL YOU WANT ON
ON YOUR COLLECTOR. (IF YOU HAVE ALREADY MADE YOUR CHOICE.)
TYPE ANY OTHER KEY IF YOU WANT TO SEE THE NEXT PAGE.

REF. NO.	TYPE OF ABSORBER	COSTS $/SQR. FT. INITIAL	ANNUAL MAINTENANCE	INSTALLATION	USEFUL LIFE	ABSORPTIVITY %	EMISSIVITY %
1	BLACK POLYETHYLENE	.03	.01	.01	5	93.0	93.0
2	COMMON BLACK PAINT	.03	.01	.02	3	98.0	98.0
3	OVEN BLACK PAINT	.04	.01	.02	5	98.0	98.0

TYPE "0" IF YOU WANT TO SEE THE BEGINNING OF THE TABLE.
TYPE THE REFERENCE NUMBER OF THE MATERIAL YOU WANT ON YOUR COLLECTOR. (IF YOU HAVE ALREADY MADE YOUR CHOICE.)
TYPE ANY OTHER KEY IF YOU WANT TO SEE THE NEXT PAGE.

APPENDIX F
SAMPLE COMPUTER PRINTOUT

SOLAR DRYING SYSTEM FOR CORN

Location: GNV
Latitude: 29.50 deg.
Longitude: 82.00 deg.

Total amount of corn dried annually 5000.00 bushels.
Amount of corn dried per batch 1000.00 bushels.
Initial moisture content is 22.00 % wet basis, (28.21 % dry basis.)
Final moisture content is 15.00 % wet basis, (17.65 % dry basis.)

Day to start drying: Month: AUGUST
Day: 1
The area of the drying facility is 320 SQR.ft.
The depth of the grain is 3.91 ft.

CHARACTERISTICS OF THE COLLECTOR

COLLECTOR TYPE II, air flows on both sides of the absorber.
COLLECTOR CROSS SECTIONAL SHAPE: semicircular.

DIMENSIONS: Length: 100.00 ft.
Width: 20.00 ft.
Height: 3.50 ft.

The inclination of the collector surface is 0.00 deg.
The orientation from the south to the east is 0.00 deg.

COLLECTOR MATERIALS

Cover: POLYETHYLENE, 4-MIL

Costs:

Initial:	0.06 $/SQR.ft.
Installation:	0.02 $/SQR.ft.
Annual maintenance:	0.01 $/SQR.ft.

Useful life: 2.00 years.

Optical properties:

Long wavelength
Transmissivity: 80.00%.

Short wavelength
Transmissivity: 88.80%.

Absorber: BLACK POLYETHYLENE

Costs:

Initial:	0.03 $/SQR.ft.
Installation:	0.01 $/SQR.ft.
Annual maintenance:	0.01 $/SQR.ft.

Useful life: 5.00 years.

Optical properties:

Long wavelength
Emissivity: 93.00%.

Short wavelength
Absorptivity: 93.00%.

Insulating material: NO INSULATION

Thickness of insulation: 1.0 inches.

Costs:

Initial:	0.05 $/SQR.ft.
Installation:	0.01 $/SQR.ft.
Annual maintenance:	0.00 $/SQR.ft.

Note: includes framing cost.

Useful life: 5.00 years.

Thermal resistance: 1.00 HR-SQR.ft/Btu.

AREAS

Cover: 2159.53 SQR.ft.
Absorber: 2000.00 SQR.ft.
Case: 2056.61 SQR.ft.

The air flow rate is 5000.00 CFM.
The mass flow rate per
unit area is 11.01 lbs/SQR.ft-h.

STARTING DATE FOR BATCH 1 AUGUST 1.

SUNRISE AT 5.35 HOURS (SOLAR TIME)
SUNSET AT 18.65 HOURS (SOLAR TIME)
THE COLLECTOR OPERATES FROM 8 TO 18 HOURS

THE TIME ALLOWED TO STORE CORN AT THE INITIAL M.C.,
BEFORE 0.5% OF THE DRY MATTER CONTENT OF CORN IS LOST,
IS 7.6 DAYS.

DAILY INFORMATION ON COLLECTOR PERFORMANCE

DAY	TOTAL HOR. RAD. Btu/ft2	TOTAL DIR. RAD. Btu/ft2	TOTAL DIFF. RAD. Btu/ft2	TOTAL USEFUL HEAT Btu/1000	AVERAGE THERMAL EFF. dec.	AVERAGE TEMP. INCREASE F	AVERAGE OUTLET TEMP. F
1.	1809.60	1073.45	736.15	901.35	0.25	15.3	97.7
2.	2040.10	1281.01	759.09	1067.46	0.26	18.3	102.4
3.	1199.80	339.24	860.56	530.78	0.22	8.9	87.6
4.	1455.50	556.60	898.90	706.68	0.24	12.0	93.2
5.	1860.20	1042.90	817.30	947.75	0.25	16.1	101.4

ENERGY CONSUMPTION:

A. By Fan: - To drive the air through the collector 102.25 KW-HR
- To drive the air through the grain 398.62 KW-HR

B. By Heater: - To heat the air 5. degrees F at night 10.17 millions Btu.
(Approximately 100.13 gallons of LPG.)

TOTAL USEFUL HEAT COLLECTED BY SOLAR COLLECTOR 25.88 million Btu.
(Approximately 254.75 gallons of LPG.)

ECONOMIC ANALYSIS
PRICES OF ENERGY :

ELECTRICITY 0.05 $/KW-HR
L.P. GAS 1.00 $/gal

COST OF COLLECTOR:

	COVER	ABSORBER	INSULATION
Initial	129.57	60.00	102.83
Installation	43.19	20.00	20.57
Maintenance	21.60	20.00	0.00

EQUIVALENT ANNUAL COST OF SOLAR COLLECTOR $ 153.

Cost of the Energy Used:

A. By Fan: - To drive the air through the collector $ 5.11
- To drive the air through the grain $ 19.93

By Heater : - To heat the air 5. degrees F at night $ 100.13

Initial Cost of the Fan $ 610.00
Useful life 15. years

Initial Cost of the Heater $ 500.00
Useful life 15. years

ANNUAL ENERGY SAVINGS DUE TO SOLAR COLLECTOR $ 254.75
NET ANNUAL ENERGY SAVINGS DUE TO SOLAR COLLECTOR $ 249.64

Assuming that the same amount of corn will
be dried each year during the useful life of the system
and an interest on the money of 10. %.

COST OF DRYING CORN 0.07 $/Bu

Based on the assumptions stated above, the equivalent annual
cost of the solar collector ($153.00) and the net annual energy
savings ($249.64),
IT IS RECOMMENDED TO INSTALL THE SOLAR COLLECTOR.

APPENDIX G
DESCRIPTION OF SUBROUTINES AND FUNCTIONS

Function KB

This function determines the percent of possible direct-normal radiation falling on the earth. The estimation of this coefficient is based on a study done by Randall and Whitson (1977) and recommended by Kreider and Kreith (1981). This value is determined by using the percent of total-horizontal radiation, K_t, which is calculated in the main program.

Subroutine DAYNUM

This routine prompts the user to input the date to start drying and based on this information, it determines the number of days within the month and the intensity of direct-normal radiation outside the earth's atmosphere, I_{ext}.

Subroutine PRINTABLES

Given the name of the file to be printed, FNAME, the number of references, N, the number of the lines printed at the bottom, NB, and the number of references printed at a time, NPAGE, the routine displays the materials used on the cover, absorber or insulation. It checks for mismatch data input by the user. After the user decides

what material he is going to use on his collector, the routine called READTABLES reads the data and stores it for further calculations.

Subroutine READTABLES

This routine reads the data for collector materials from the tables shown to the user. The arguments for this routine are the name of the file (cover, absorb or insulati), the number of lines used for headings, the number of references and the reference number input by the user.

Function AVGTEMP

The dry bulb average ambient temperature is calculated for the first ten days of the drying period. The purpose of this variable is to determine the maximum time allowed to dry each batch of corn. This average temperature is calculated for every batch.

Subroutine AREA

Given the cross sectional shape of the collector, SHAPE, and the dimensions of the collector, this routine calculates the following variables:

Absorber area: AABS

Area of the bottom of the collector: ABOT

Cover area: ACOV

Cross sectional area of collector: ACROSS

Perimeter of the cross sectional shape: PER

The equations used to calculate these areas are shown in figures 3 to 6.

Function TRANS

This function has the coefficients to calculate the short wavelength transmissivity of the different covers as a function of the angle of incidence. The arguments for this function are the reference number, REF, and the incident angle, ANGLE. The calculation of this angle is done by a polynomio of fourth degree. These polynomials are shown in appendix C.

Subroutines SUBOUT1 and SUBOUT2

These are the two main routines responsible for creating the output file called USERFILE. The variables written by SUBOUT1 are mainly the inputs selected by the user. SUBOUT2 writes the costs of the drying system. Data from the performance of the collector and the final moisture content for each batch is written from the main program.

Subroutine AIRFLOW

This routine prompts the user with an airflow rate based on the amount of bushels per batch that are dried. The user has the option to use this rate (5 CFM/Bu) or choose a different value.

Function FANCOLLE

This function calculates the energy per hour used by the fan to drive the air through the collector. A pressure drop of 62.5 Pa (0.25 in of water) has been assumed.

Function FANGRAINE

This function calculates the energy required for the fan to move the air through the grain. Pressure drop through the grain is based on an empirical equation by Hukill and Shedd (1955). The fan efficiency is assumed to be 60%.

Function EMC

This function calculates the equilibrium moisture content (dry basis) of the grain. The equation used here was proposed by Thompson (1967). Inputs for this equation are relative humidity, RH, and air temperature at the plenum, TO.

Subroutine INPUTS1

This routine asks the user how many degrees F the air temperature is going to be increased and then prompts the user for costs of the electricity and LP gas. The user has the option to leave these values or change them.

Functions WBTODB and DBTOWB

These functions determine the moisture content dry basis from the moisture content wet basis and the moisture content wet basis from the moisture content dry basis, respectively.

Subroutine DATE

After the first batch, the month, the number of days remaining in that month and the normal-direct extraterrestrial radiation is are updated.

Subroutine READWEATHER

This routine reads the weather data from the files named with the monthname to which it corresponds. Weather data is read for a whole month at a time. If the starting date of drying is after the fifteenth day of the month then the last fifteen days of weather data of the month at which drying starts and fourteen days of the following month will be read and stored on the ram. Weather data is read at the beginning of each batch so maximum time allowed to dry each batch ought to be no more than thirty days.

Subroutine TIMED1

This routine reads the mechanical damage of the grain which is entered by the user. A default value of 30% is used in case the user does not have a better estimate. A factor is calculated based on this percentage of mechanical damage and the theoretical maximum time allowed to dry the corn will be multiplied by this factor. The user can input a maximum time allowed for running the model. However, there will be a warning written on the final file.

Subroutine DAYS

The theoretical maximum time allowed to dry the corn is calculated by using some curves presented by Steele et al.(1969). The curves show the relation between storage temperature and permissible storage time. The permissible storage time is defined as the maximum time the grain can stand at certain temperature and moisture content without loosing more than 0.5 percent of its total dry matter.

Subroutines COLT1, COLT2 and COLT3

The algorithm used to determine the collector temperatures requires the roots of a set of nonlinear equations. These equations are shown in the development chapter for collector type I and in appendices A and B for collectors type II and III. In these three routines the coefficients of the function are calculated. Then using the values for the temperatures, first guessed by the routine TEMPGENERATOR and then updated by each iteration, the functions and their partial derivatives are calculated.

Subroutines CONVECT1, CONVECT2 and CONVECT3

These routines calculate the film convection coefficients of the inside the collectors, i.e., between the air going through the collector and the different layers. These coefficients are shown on Figures 13, 18 and 19 for collector types I, II and III.

Subroutine SUSPENDED

This routine determines the cross sectional area, the hydraulic radius, the Reynold's number and the mass flow rate per hour for channels 1 and 2 of collector type II. The only two shapes for the suspended absorber are semicircular and rectangular. The air velocity is equal on both channels.

Subroutine COLMATERIALS

This routine determines the thermal and optical properties of the collector materials. It converts input optical properties from percentage into decimal. Finally, it calculates or estiates the remaining properties required in the model.

Subroutine PERFORMANCE

The determination of collector performance uses the Newton-Raphson method to find the roots of the equations for either collector type. Figure 2 shows the flowchart for this routine. It starts defining some constants and initiating some variables. Then the PERFORMANCE routine calls the proper routines depending upon the collector type to calculate the values for F1 and F2 (and F3 if it is collector type II) and their partial derivatives. The signs for values of the functions are changed and the routine GAUSSJ is used to determine the temperature increments required. If at least one of these increments is larger than the maximum tolerance then a new trial is required. If all the temperature increments are smaller than the maximum tolerance, the average air temperature at that segment is

calculated by using the routine TEMPF. The outlet air temperature is calculated and the process is repeated for the next collector segment. When all the collector segments are calculated, the hourly useful heat and thermal efficiency are calculated. These values are passed to the main program.

Subroutine DRYING

This routine determines the average moisture content of the grain. The moisture ratio is determined by the following equation.

$$MR = \frac{1}{D} \ln \frac{e^{D} + e^{\theta} - 1}{e^{\theta}}$$

where

D = depth factor, adimensional.

θ = time factor, adimensional.

$$D = \frac{L\ K\ \rho_{corn}\ (M_0 - M_e)}{G\ C_p\ (T_0 - T_e)}\ Y$$

$$\theta = K\ t$$

and

$$MR = \frac{M - M_e}{M_0 - M_e}$$

$$K = \left(\frac{P_s}{14.22}\right)^{M} \left(\frac{V}{2.82}\right)^{N}$$

where

B, M, N = constants, adimensional.

P_s = saturation vapor pressure of the air, psi.

V = air velocity through the drying bin, ft/s.

L = heat of vaporization of corn at 20% m.c., d.b..

K = drying constant, 1/h.

ρ_{corn} = density of corn at 15.5% M.C., w.b, lb/ft^3.

G = air mass flow rate, lb/h.

C_p = specific heat of the air, Btu/lb-F.

T_0 = air temperature, F.

T_e = equilibrium temperature of the air, F.

M_0 = moisture content, d.b., of grain, decimal.

M_e = equilibrium moisture content d.b., decimal.

Y = total depth of grain, ft.

The routine DRYING calculates first the equilibrium moisture content of the grain, M_e, and the saturation vapor pressure, P_s. These values are calculated by using the functions EMC and PSDBDP, respectively. The velocity and the drying constant K are calculated next. The equilibrium temperature, T_e, which is the air leaving the grain is assumed to leave at saturation. Hence, the temperature of this air is the wet bulb temperature. This value is calculated by using the function WBDBDP. After all the coefficients are calculated, the moisture ratio can be evaluated. The specific heat of the air and the air density are assumed constant and their respective values are

0.24 Btu/lb-F and 0.0734 lb/ft^3, respectively. These values are for temperatures of 29 C (52 F). These values vary less than 5 percent within a range of plus or minus 17 C (30 F).

Subroutine ECANALYSIS

This routine calculates the cost to dry one bushel of corn from the initial to the final moisture content indicated by the user. The cost per unit area of each collector material is multiplied by its respective area and the value is spread over their useful life in order to obtain an annual cost (each one individually). The initial cost of the fan and heater as well as the energy used during a year is also calculated and then the total cost of running the system is determined. This cost is divided by the total amount of corn dried during the year to give the unit cost of drying.

Function ANUAL

Given the present cost of an item, the interest on the money invested and the useful life this function calculates the annual equivalent cost.

Subroutine SEARCH

This routine uses the bisection method to find the root of a function between two limits. The name of the function as well as the two limits are entered in the argument. The routine tests first if the product of the functions of the two limits is positive. If it is the routine calculates the absolute value of the difference between

the two limits. If the difference is less than the maximum error allowed, EPS, the routine gives the arithmetic average as the answer. If that difference is higher than EPS a message of no convergence is displayed on the screen.

Function PSDB

The saturation vapor pressure for the temperature entered as the argument is calculated.

Function RHDBDP

The relative humidity is defined as the ratio of the vapor pressure to the vapor pressure at saturation corresponding to the dry bulb temperature input. To calculate these two values, the saturation vapor pressure of the dew point temperature and the dry bulb temperature are calculated and the ratio of the first value to the second times one hundred is relative humidity.

Function WBDBDP

This function determines the wet bulb temperature. Since the determination of this temperature is an iterative process, it uses the routine SEARCH to do so. The arguments passed from WBDBDP to SEARCH are dry bulb temperature, dew point temperature, the upper and lower guess for the wet bulb temperature and the function WBDBP1 which is the equation that gives the magnitude of the error for the guess.

Function WBDBP1

This function tests whether the wet bulb temperature guessed is the correct one or not. To be correct the following equality will meet.

$$P_{swb} - P_v = B\ (T_{wb} - T)$$

where

$$B = \frac{0.2405\ (P_{vs\ wb} - P)\ (1 + 0.15577\ P_v / P)}{0.62194\ h'_{fg}}$$

$$459.69 < T < 959.69$$

$P_{vs\ wb}$ = saturation vapor pressure of wet bulb temperature, psi.

P_v = vapor pressure of dry bulb temperature, psi.

P = barometric pressure, psi.

T_{wb} = wet bulb temperature, R.

T = dry bulb air temperature, R.

h'_{fg} = latent heat of vaporization at T_{wb}, Btu/lb.

The terms of the first equation are put on one side so the equation is equated to zero. This equation is calculated by this function.

Function BPVWB

This function calculates the value of B from the function WBDBP1.

Function HLDB

Given the dry bulb temperature, the latent heat of vaporization is calculated with this function.

APPENDIX H
LIST OF VARIABLES

A11	Real, coefficient for end functions on collectors, COLT1, COLT2 and COLT3.
A12	Real, coefficient for end functions on collectors, COLT1, COLT2 and COLT3.
A13	Real, coefficient for end functions on collector, COLT2.
A1S	Real, short wavelength absorptivity of cover, dec., COLMATERIALS.
A21	Real, coefficient for end functions on collectors, COLT1, COLT2 and COLT3.
A22	Real, coefficient for end functions on collectors, COLT1, COLT2 and COLT3.
A23	Real, coefficient for end function on collector, COLT2.
A2S	Real, short wavelength absorptivity on collector, dec., COLMATERIALS.
A31	Real, coefficient for end function on collector, COLT2.
A32	Real, coefficient for end function on collector, COLT2.
A33	Real, coefficient for end function on collector, COLT2.
A3S	Real, short wavelength absorptivity on case (collector type II), dec., COLMATERIALS.
AABS	Real, absorber area, ft^2, AREA.
ABOT	Real, case area, ft^2, AREA.
ABSABS	Real, absorptivity of absorber, %, READTABLES.
ABSANU	Real, annual cost of absorber, $\$/ft^2$, READTABLES.
ABSEMIS	Real, emissivity of absorber, %, READTABLES.

ABSINI	Real, initial cost of absorber, $/ft^2, READTABLES.
ABSINS	Real, installation cost of absorber, $/ft^2, READTABLES.
ABSMAT	Character*18, absorber material, READTABLES.
ABSNO	Real, absorber area per segment, ft^2, AREA.
ABSYRS	Real, useful life of absorber material, years, READTABLES.
ACOV	Real, cover area, ft^2, AREA.
ACROSS	Real, cross sectional area of collector, ft^2,AREA.
AESAV	Real, annual energy savings, ECANALYSIS.
AIRMASS	Real, air mass flow rate, #/min, MAIN.
AIRVEL	Real, air velocity through collector, ft/min, MAIN.
AVGDEFF	Real, average daily efficiency of collector, dec., MAIN.
AVGDT	Real, average air temperature increase through collector, F, MAIN.
AVGMC	Real, average moisture content dry basis, dec., DRYING.
AVGTOUT	Real, average temperature of the air after passing the collector, F, PERFORMANCE.
ALT	Real, altitude angle, radians, MAIN.
AVMCWB	Real, average moisture content wet basis, dec., DRYING.
AW	Real, orientation of collector, deg., MAIN.
AWRAD	Real, orientation of collector, radians, MAIN.
AZIM	Real, azimuth angle, radians, MAIN.
B11	Real, coefficient for end function on collector, COLT1, COLT2 and COLT3.
B12	Real, coefficient for end function on collector, COLT1, COLT2 and COLT3.
B13	Real, coefficient for end function on collector, COLT2.
B21	Real, coefficient for end function on collector, COLT1, COLT2 and COLT3.

B22	Real, coefficient for end function on collector, COLT1, COLT2 and COLT3.
B23	Real, coefficient for end function on collector, COLT2.
B31	Real, coefficient for end function on collector, COLT2.
B32	Real, coefficient for end function on collector, COLT2.
B33	Real, coefficient for end function on collector, COLT2.
BU	Real, number of bushels to dry per batch, MAIN.
C	Real, coefficients of the linear system of equations to be solved, GAUSS.
C1	Real, coefficient for end function on collector, COLT1, COLT2 and COLT3.
C2	Real, coefficient for end function on collector, COLT1, COLT2 and COLT3.
C3	Real, coefficient for end function on collector, COLT2.
CFM	Real, airflow rate through collector, CFM, AIRFLOW.
CFMBU	Real, airflow rate per bushel, CFM/Bu, AIRFLOW.
CITYNAME	Character*20, name of location where the solar system is located.
COEF	Real, dummy variable used to calculate bulk temperature of the air, TEMPF.
COEF1	Real, dummy variable used to calculate bulk temperature of air channel 1 on collector type II, TEMPF.
COEF2	Real, dummy variable used to calculate bulk temperature of air channel 2 on collector type II, TEMPF.
COLLKW	Real, energy required by the fan to drive the air through the collector, Kw/h, MAIN.
CORNBU	Real, cost to dry from initial to final moisture content one bushel of corn, $/Bu, ECANALYSIS.
COV1MAT	Character*18, cover material line 1.
COVMAT2	Character*18, cover material line 2.

COVANU Real, annual cost of cover, $/ft^2, READTABLES.

COVEMI Real, long wavelength emissivity of cover, %, READTABLES.

COVFUNCT Character*6, name of the function used to calculate the short wavelength as a function of the incident angle for each specific material, READTABLES.

COVINI Real, initial cost of the cover, $/ft^2, READTABLES.

COVINS Real, installation cost of cover, $/ft^2, READTABLES.

COVTL Real, average long wavelength transmissivity of the cover, %, READTABLES.

COVTS Real, average short wavelength transmissivity of the cover, %, READTABLES.

COVYRS Real, useful life of cover, years, READTABLES.

CP Real, specific heat of the air, Btu/#-F, MAIN.

DAY Real, day of the month, MAIN.

DAYN Real, Julian day, MAIN.

DAYS1 Real, dummy variable to determine any change in time allowed to dry grain, TIMED1.

DEC Real, declination angle, deg., MAIN.

DECRAD Real, declination angle, radians, MAIN.

DEGALT Real, altitude angle of sun, deg., MAIN.

DEGAZIM Real, azimuth angle, deg., MAIN.

DEGHS Real, hour angle, deg., MAIN.

DEGINC Real, inclination solar angle, deg., MAIN.

DEGRAD Real, conversion factor from degrees to radians, MAIN.

DELTARAD Real, dummy variable used to calculate declination, DELTA.

DELTAT Real, temperature increment through collector at night, F, MAIN.

DEN Real, dummy variable used to regroup values, COLT1 and COLT2.

DEN1	Real, dummy variable used to regroup values, COLT2.
DEN2	Real, dummy variable used to regroup values, COLT2.
DEPTH	Real, drying bin depth, ft, MAIN.
DF	Real, partial derivative of end functions for collector performance, COLT1, COLT2 and COLT3.
DF11	Real, partial derivative of end function for collector performance, COLT1, COLT2 and COLT3.
DF12	Real, partial derivative of end function for collector performance, COLT1, COLT2 and COLT3.
DF13	Real, partial derivative of end function for collector performance, COLT1, COLT2 and COL3.
DF21	Real, partial derivative of end function for collector performance, COLT1, COLT2 and COLT3.
DF22	Real, partial derivative of end function for collector performance, COLT1, COLT2 and COLT3.
DF23	Real, partial derivative of end function for collector performance, COLT1, COLT2 and COLT3
DF31	Real, partial derivative of end function for collector performance, COLT1, COLT2 and COLT3.
DF32	Real, partial derivative of end function for collector performance, COLT1, COLT2 and COLT3.
DF33	Real, partial derivative of end function for collector performance, COLT1, COLT2 and COLT3.
DH	Real, hydraulic radius, ft, MAIN.
DH1	Real, hydraulic radius for channel 1 on collector type II, ft, SUSPENDED.
DH2	Real, hydraulic radius for channel 2 on collector type II, ft, SUSPENDED.
DPPRIME	Real, pressure drop per foot depth on grain, in. water, FANGRAINE.
DQO	Real, daily useful heat recovered from the collector, Btu, MAIN.

E12L	Real, long wavelength emissivity factor, dec., COLMATERIALS.
E1L	Real, long wavelength emissivity, dec., COLMATERIALS.
E23L	Real, long wavelength emissivity factor, dec., COLMATERIALS.
E2L	Real, long wavelength emissivity, dec., COLMATERIALS.
E3L	Real, long wavelength emissivity, dec., COLMATERIALS.
EFF	Real, thermal efficiency of collector, dec., PERFORMANCE.
ELCT	Real, cost of the electircity, $/Kw, MAIN.
F	Real, end function for collector performance, COLT1, COLT2 and COLT3.
FACTOR	Real, multiplier to compensate for mechanical damage of corn, TIMED1.
FANINI	Real, initial cost of the fan, MAIN.
FMCDB	Real, final moisture content of corn dry basis, MAIN.
FMCWB	Real, final moisture content of corn wet basis, MAIN.
G	Real, air mass per unit of absorber area, #/ft^2, MAIN.
G1	Real, air mass going through channel 1, ft^2/h, SUSPENDED.
G2	Real, air mass going through channel 2, ft^2/h, SUSPENDED.
GCROSS	Real, air mass going through whole collector, ft^2/h, MAIN.
H1	Real, convection coefficient between air going through collector and layer 1, Btu/ft^2-h-F, CONVECT1, CONVECT2 and CONVECT3.
H2	Real, convection coefficient between air going through collector and layer 2, Btu/ft^2-h-F, CONVECT1 and CONVECT3.
H2P	Real, convection coefficient between air going throuh channel 1 and the absorber, Btu/ft^2-h-F, CONVECT2.
H2PP	Real, convection coefficient between air going through channel 2 and the absorber, CONVECT2.

H3 Real, convection coefficient between air going through channel 2 and the bottom, CONVECT2.

HBOTTOM Real, convection coefficient between outside air and outside surface of the collector case, Btu/ft^2-h-F, COLMATERIALS.

HEATERLPG Real, hourly energy used by heater, Btu, MAIN.

HEATINI Real, initial cost of the heater, MAIN.

HEATYR Real, useful life of heater, years, MAIN.

HPFAN Real, power required by the fan, HP, MAIN.

HS Real, solar hour angle, radians, MAIN.

HT Integer, hourly time, MAIN.

HTABLE Character*80, headings of the tables (materials), MAIN.

HW Real, wind convection coefficient, Btu/ft^2-h-F, PERFORMANCE.

IB Real, direct radiation incident on horizontal surface, Btu/ft^2-h,MAIN.

IBT Real, direct radiation incident on collector surface, Btu/ft^2-h, MAIN.

ID Real, diffuse radiation incident on horizontal surface, Btu/ft^2-h, MAIN.

IDAN Integer, closest hour after dawn, MAIN.

IDAY Integer, day of the month, READWEATHER.

IDT Real, diffuse radiation incident on collector surface, Btu/ft^2-h, MAIN.

IET Real, extraterrestrial normal radiation, Btu/ft^2-h, DAYNUM and DATE.

IMCDB Real, initial moisture content dry basis, dec., MAIN.

IMCWB Real, initial moisture content wet basis, dec., MAIN.

INCID Real, incident solar angle, radians, MAIN.

INSANU Real, annual insulation cost, \$/ft^2, READTABLES.

INSINI	Real, initial cost of insulation material, $\$/ft^2$, READTABLES.
INSINS	Real, installation cost of insulation material, $\$/ft^2$, READTABLES.
INSMAT	Character*18, insulation material, READTABLES.
INSRIN	Real, thermal resistance of insulation, ft^2-h/Btu-in, READTABLES.
INSTHICK	Real, insulation thickness, in, READTABLES.
INSYRS	Real, useful life of insulation, years, READTABLES.
INTEREST	Real, interest on the money invested, %, MAIN.
ISEG	Integer, segment number (of collector), PERFORMANCE.
ITERMAX	Integer, maximum number of iterations, GAUSS and PERFORMANCE.
ITIME	Integer, hour of the day, READWEATHER.
JULIAN	Integer, day of the year, READWEATHER.
K	Real, thermal conductivity of the air, 0.0153 Btu/ft-h-F, MAIN.
K	Real, drying constant, 1/h, DRYING.
KB1	Real, percentage of the total possible direct radiation, MAIN.
KD	Integer, dummy variable keeps track of the number of days after the first day of the drying batch.
KD1	Integer, last day of drying batch, MAIN.
KDAWN	Integer, hour at which solar collector starts working, MAIN.
KDL	Integer, maximum time allowed to dry corn, DAYS.
KT	Real, percentage of maximum total radiation incident on a horizontal surface, MAIN.
L	Real, distance from the collector entrance, ft, CONVECT1, CONVECT2 and CONVECT3.

L1	Real, collector length, ft, MAIN.
L2	Real, collector width, ft, MAIN.
L3	Real, collector height, ft, MAIN.
LAMBDA	Real, relaxation coefficient, GAUSS.
LASTDM	Integer, last day of the month, DAYNUM and DATE.
LAT	Real, latitude, deg., MAIN.
LATRAD	Real, latitude, radians, MAIN.
LBATCH	Integer, batch number, MAIN.
LPGAS	Real, cost of LP gas, $/gl, MAIN.
LPGSAVE	Real, amount of LP gas saved, MAIN.
M	Real, constant, DRYING.
MCWB	Real, moisture content wet basis, dec., DAYS.
MD	Real, mechanical damage, %, TIMED1.
ME	Real, equilibrium moisture content dry basis, dec., DRYING.
MN	Integer, month number, DAYNUM and DATE.
MONTH	Character*10, month, MAIN.
MU	Real, absolute viscocity of the air, 0.045 #/ft-h, MAIN.
N	Real, constant, DRYING.
N	Real, number of years, ANUAL.
N	Integer, number of references in the table, PRINTABLES.
N1	Integer, dummy variable, keeps track of last reference number on the page, PRINTABLES.
NB	Integer, number of lines at bottom of table, PRINTABLES.
NBATCH	Integer, number of batches to be dried, MAIN.
NCHECK	Integer, dummy variable check for reference number entered by the user, PRINTABLES.

NEQ	Integer, number of equations, MAIN.
NEWTON	Integer, flag to determine if SIGMA values are larger than the maximum tolerance, PERFORMANCE.
NH	Integer, number of lines used for headings, PRINTABLES.
NINF	Integer, Nusselt number for stabilized flow, CONVECT1, CONVECT2 and CONVECT3.
NO	Integer, number of segments in which the collector is divided to calculate the temperatures, MAIN.
NPAGE	Integer, number of references printed at a time, PRINTABLES.
NTABLE	Integer, dummy variable used to determine how many lines per reference material, PRINTABLE.
NU1	Real, dummy variable, CONVECT2 and CONVECT3.
NU2	Real, dummy variable, CONVECT2 and CONVECT3.
NU11LOCAL	Real, local Nusselt number between inside air and cover, CONVECT2.
NU23LOCAL	Real, local Nusselt number between inside air channel 2 and case, CONVECT2.
NU2LOCAL	Real, local Nussel number between absorber and inside air, CONVECT3.
NU3	Real, dummy variable, CONVECT2.
NU3LOCAL	Real, local Nusselt number between inside air channel 2 and case, CONVECT2.
NUINF	Real, Nusselt number for stabilized flow, CONVECT1 and CONVECT3.
NUINF1	Real, Nusselt number for stabilized flow in channel 1, CONVECT2.
NUINF2	Real, Nusselt number for stabilized flow in channel 2, CONVECT2.
NULOCAL	Real, local Nusselt number, CONVECT1.
NUMBER	Integer, dummy variable used to read the reference material chosen by the user, PRINTABLES.

P	Real, present value, ANUAL.
P1	Real, dummy variable, SEARC1, SEARCH and PSDB.
P1	Real, perimeter of cross section, ft,SUSPENDED.
P2	Real, perimeter for cross section channel 2, SUSPENDED.
PATM	Real, atmospheric pressure, 14.7psi, MAIN.
PER	Real, perimeter of cross section area, AREA.
PI	Real, constant, 3.141593.
PR	Real, Prandtl number, 0.7, CONVECT1, CONVECT2 and CONVECT3.
PS	Real, saturation vapor pressure, psi, PSDB.
PV	Real, vapor pressure, psi, BPVWB.
QO	Real, incident insolation on cover surface, Btu/ft^2-h, MAIN.
QRAD	Real, total hourly horizontal solar radiation, Btu/ft^2-h, READWEATHER.
QUSEFUL	Real, hourly useful heat recovered by the air going through the collector, PERFORMANCE.
R	Real, collector end function values used on GAUSS routine, PERFORMANCE.
RABOT	Real, ratio of case over absorber area, AREA.
RACOV	Real, ratio of cover over absorber area, AREA.
RADDEG	Real, conversion factor radians to degrees, MAIN.
RADIUS	Real, radius of semicircular cross section, ft, AREA.
RBOTTOM	Real, thermal resistance of the collector case, ft^2-h-F/Btu, COLMATERIALS.
RE	Real, Reynolds number, MAIN.
RE1	Real, Reynolds number for cross section area channel 1 (collector type II), SUSPENDED.
RE2	Real, Reynolds number for cross section area channel 2 (collector type II), SUSPENDED.

REF	Character*6, material name, TRANS.
RH	Real, relative humidity, dec., DBRH.
RHUM	Real, ambient relative humidity, %, READWEATHER.
RO12S	Real, short wavelength reflectivity factor, dec., COLMATERIALS.
RO1S	Real, short wavelength cover reflectivity, dec., COLMATERIALS.
RO2S	Real, short wavelength absorber reflectivity, dec., COLMATERIALS.
ROAIR	Real, air density, 0.0734 #/ft3, MAIN.
ROCORN	Real, corn bulk density, 47.32 #/ft3, DRYING.
ROGROUND	Real, reflectivity of the ground, 0.20, MAIN.
S1	Real, low limit for search algorithm, SEARCH and SEARC.
S2	Real, high limit for search algorithm, SEARCH and SEARC1.
SHAPE	Real, cross sectional shape of collector, MAIN.
SIGMA	Real, inclination angle of collector with respect to horizontal, MAIN.
SIGMA	Real, temperature increment for collector end functions, PERFORMANCE.
SIGMA	Real, Stephan Boltzman constant for radiation, 0.1714E-08 ft^2-h-R^4/Btu, COLT1, COLT2 and COLT3.
SIGMARAD	Real, inclination angle of collector with respect to horizontal, radians, MAIN.
SRTIME	Real, sunrise, h, MAIN.
SSTIME	Real, sunset time, h, MAIN.
T1	Real, temperature at layer 1, F, TEMPGENERATOR and PERFORMANCE.
T1	Real, low partial result on ith iteration, SEARCH and SEARC1.
T12	Real, dummy variable to test results, SEARCH and SEARC1.

T2	Real, high partial result on ith iteration, SEARCH and SEARC1.
T2	Real, temperature on layer 2, F, TEMPGENERATOR PERFORMANCE.
T3	Real, temperature of layer 3, F, TEMPGENERATOR, PERFORMANCE.
TABLE	Character*80, dummy variable used to show materials, PRINTABLES.
TAMB	Real, ambient temperature, R, COLT1, COLT2 and COLT3.
TANUABS	Real, total annual cost of absorber, $, ECANALYSIS.
TANUCOV	Real, total annual cost of cover, $, ECANALYSIS.
TANUINS	Real, total annual insulation cost, $, ECANALYSIS.
TAU1L	Real, long wavelength transmissivity of cover, dec., COLMATERIALS.
TAU1QO	Real, total solar radiation transmitted through the cover, Btu/ft^2-h, MAIN.
TAULONG	Real, long wavelength transmissivity through the cover, %, COLMATERIALS.
TAUSHORT	Real, short wavelength transmissivity of cover, COLMATERIALS.
TCEHEAT	Real, total cost of energy used by heater, MAIN.
TDB	Real, dry bulb ambient temperature, F, MAIN.
TDP	Real, dew point temperature, F, MAIN.
TDQUSEFUL	Real, total daily useful heatrecover by air, Btu, MAIN.
TE	Real, equilibrium temperature, F, DRYING.
TEFANCOLLE	Real, total energy used by the fan to drive the air through the collector, Kw-h, MAIN.
TFANECOST	Real,total cost of energy used by the fan, MAIN.
TFANGRAINE	Real, total energy used by the fan to drive the air though the grain, Kw-h, MAIN.

TGRAINECOST Real, total cost of energy used by the fan to drive the air through the grain, $, MAIN.

TI Real, dummy variable, SEARCH and SEARC1.

TIDIFF Real, total daily diffuse radiation incident on collector surface, Btu/ft^2, MAIN.

TIDIR Real, total daily direct radiation incident on collector cover, Btu/ft^2, MAIN.

TIHOR Real, total daily horizontal radiation, Btu/ft^2, MAIN.

TIME Real, hour, READWEATHER.

TIMECOLLE Real, number of hours in which air has gone through the collector, h, MAIN.

TIMEHEAT Real, number of hours in which heater has been on, h, MAIN.

TIN Real, air temperature at inlet of ith segment, F, PERFORMANCE.

TIN1 Real, air temperature at inlet of ith segment of channel 1, F, PERFORMANCE.

TIN2 Real, air temperature at inlet of ith segment of channel 2, F, PERFORMANCE.

TINIABS Real, total initial cost of absorber, $, ECANALYSIS.

TINICOV Real, total initial cost of cover, $, ECANALYSIS.

TINIINS Real, total initial cost of insulation, $, ECANALYSIS.

TINSABS Real, total installation cost of absorber, $, ECANALYSIS.

TINSCOV Real, total installation cost of cover, $, ECANALYSIS.

TINSINS Real, total installation cost of insulation, $, ECANALYSIS.

TO Real, air temperature at plenum, F,MAIN.

TOL Real, maximum tolerance, GAUSS.

TOLNRAP Real, maximum tolerance, PERFORMANCE.

TOTBU Real, total amount of cor dried annually, Bu, MAIN.

TOTLPE	Real, total amountof energy used by heater, Bu/1.0E6, MAIN.
OTLPGAS	Real, total LP gas used, gl, MAIN.
TOTQ	Real, total useful heat save per year, Btu/1.0E6, MAIN.
TOUT	Real, outlet air temperature from collector, F, PERFORMANCE.
TOUT1	Real, outlet air temperature from collector (channel 1), F, PERFORMANCE.
TOUT2	Real, outlet air temperature from collector (channel 2), F, PERFORMANCE.
TSKY	Real, sky temperature, R, PERFORMANCE.
TYPE	Real, collector type, MAIN.
V	Real, air velocity at drying bin, ft/sec, DRYING.
VEL	Real, air velocity through drying bin, ft/min, FANGRAINE.
VOLBIN	Real, bin volume, Bu, MAIN.
WB	Real, wet bulb temperature, F, WBDBDP.
WI	Real, dummy variable, SEARCH and SEARC1.
WIND	Real, wind velocity, mph, READWEATHER.
X	Real, dummy variable, DBTOWB and WBTODB.
X1	Real, dummy variable, AREA.
X2	Real, dummy variable, SUSPENDED.
X3	Real, dummy variable, AREA.
XNEW	Real, new guess for unknown, GAUSS.
XOLD	Real, old guess for unknown, GAUSS.
Y	Real, depth of corn on drying bin, CORNDEPTH.

APPENDIX I
PROGRAM SOURCE CODE

```
C     PROGRAM SOLDRY

      COMMON/ABSMATERIALS/ABSABS,ABSANU,EMIS,ABSINI,ABSINS,
     $        ABSMAT,ABSYRS
      COMMON/COVMATERIAL/COVANU,COVEMIS,COVFUNCT,COVINIT,COVINS,
     $        COV1MAT,COV2MAT,COVTL,COVTS,COVYRS
      COMMON/INSMATERIAL/INSANU,INSINI,INSINS,INSMAT,INSRIN,
     $        INSTHIK,INSYRS
      COMMON/INSOLATION/IBT,IDT,INCID,DEGINCID
      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/MATCOLT/A1S,A2S,A3S,E1L,E2L,E12L,E23L,
     $        RBOTTOM,RO1S,RO12S,TAULONG,TAUSHORT
      COMMON/AIRVARIABLES/AIRMASS,AIRVEL,CFM
      COMMON/AIRPROPERTIES/CP,K,MU,ROAIR
      COMMON/PERFVAR/HW,QO,TAU1QO,TSKY
      COMMON/COLTOUT/EFF,QUSEFUL,TOUT
      COMMON/DIMENSIONS/NO,L1,L2,L3
      COMMON/ATMPRES/PATM
      COMMON/MCLAYER/AVGMC
      COMMON/TCOST/COSTCOLL1,TANUALC,CORNBU
      COMMON/TENERGY/TEFAN,TFANGRAINE,TOTLPGAS,LPGSAV
      COMMON/FANHEAT/FANINI,FANYRS,HEATINI,HEATYRS,TCEHEAT,
     $              TCFANCOLLE,TCFANGRAINE
      COMMON/TOTCOV/TINICOV,TINSCOV,TANUCOV
      COMMON/TOTABS/TINIABS,TINSABS,TANUABS
      COMMON/TOTINS/TINIINS,TINSINS,TANUINS
      COMMON/WEATHER/JULIAN(31),TIME(31,24),WIND(31,24),
     $              QRAD(31,24),RHUM(31,24),TEMP(31,24)
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2
      COMMON/TEMPERATURES/T1,T2,T3,TF,TF1,TF2
      COMMON/PARTDER/C(3,3)

      CHARACTER*72 WORD(30),ATYPE(15),ASHAPE(17)
      CHARACTER*19 INSHAPE,INTYPE
```

```
      CHARACTER*18 ABSMAT
      CHARACTER*18 COV1MAT,COV2MAT
      CHARACTER*6 COVFUNCT
      CHARACTER*18 INSMAT
      CHARACTER*80 HTABLE(15)
      CHARACTER*10 MONTH(12)
      CHARACTER*8 FNAME
      CHARACTER*20 CITYNAME
      CHARACTER*18 FILE1,FILE2

      REAL*4 INSTHIK,INSINI,INSINS,INSANU,INSYRS,INSRIN
      REAL*4 HS,HSR,IB,IBT,ID,IDT,IEXT,IMC,INCID
      REAL*4 IMCDB,IMCWB
      REAL*4 KB,KB1,KT,LA,LAT,LATRAD,LOLONG,MD
      REAL*4 CP,K,MU,PI,ROAIR
      REAL*4 L1,L2,L3
      REAL*4 MO
      REAL*4 HEATERLPG
      REAL*4 LPGAS,LPGSAV
      REAL*4 MBAR(10)
      REAL*4 INTEREST
      REAL*4 H1,H2P,H2PP,H3


      DATA MONTH/'JANUARY','FEBRUARY','MARCH','APRIL','MAY',
     $           'JUNE','JULY','AUGUST','SEPTEMBER','OCTOBER',
     $           'NOVEMBER','DECEMBER'/


      WRITE(1,*)' ENTER TEMP.OUT'
     READ(1,123) FILE1

      WRITE(1,*)' ENTER USERFILE'
      READ(1,123) FILE2

123   FORMAT(A18)

C     .....OPENING FILES.....


      OPEN(11,FILE = FILE1)
      OPEN(12,FILE='TEMF.OUT')
      OPEN(16,FILE=FILE2)


C     .....INPUTS.....
```

```
C     .....CONSTANTS.....

C     .....NATURAL.....
C      PI = 3.141593
      DEGRAD = 180./PI
      RADDEG = PI/180.


C     .....ASSUMED.....
      CP = 0.24
     ROAIR = 0.0734
      MU = 0.045
      K = 0.0153
      PATM = 14.7
      ROGROUND = 0.20

C     .....PROGRAM.....
      NO = 5
      FANYRS = 15.
      HEATYRS = 15.

C     .....INPUT LOCATION OF THE DRYING FACILITY.....

      WRITE(1,*)' INPUT THE NAME OF THE PLACE WHERE YOU WANT',
     $          ' THE DRYING SYSTEM.'
      READ(1,30) CITYNAME
      WRITE(1,*)' INPUT LATITUDE:'
      READ(1,*) LAT
      WRITE(1,*)' INPUT LONGITUDE:'
      READ(1,*) LOLONG


C     .....INPUT INCLINATION AND ORIENTATION USING FILE 'INCLINATION'
C          FOR EXPLANATIONS.....

      OPEN (90,FILE='INCLINATION')
      READ(90,1010) (WORD(I),I=1,30)
      CLOSE(90)
15    WRITE(1,1010) (WORD(I),I=1,15)


C     .....INPUT ORIENTATION, DEGREES.....

      READ(1,*) AW
      AWRAD = AW*RADDEG

      WRITE(1,1010) (WORD(I),I=16,30)


C     .....INPUT INCLINATION, DEGREES.....
```

```
      READ(1,*) SIGMA
      SIGMARAD = SIGMA*RADDEG


C     .....INPUT COLLECTOR TYPE.....

      OPEN(99,FILE='COLTYPE')
      READ(99,1010) (ATYPE(I),I=1,15)
      CLOSE(99)
133   WRITE(1,1010) (ATYPE(I),I=1,15)
      READ(1,*) TYPE

      IF(TYPE.NE.1.0.AND.TYPE.NE.2.0.AND.TYPE.NE.3.0) THEN
         WRITE(1,*)' PLEASE CHECK THE TYPE NUMBER.'
         GO TO 133
      ENDIF


      OPEN(100,FILE='COLSHAPE')
      READ(100,1010)  (ASHAPE(I),I=1,17)
      CLOSE(100)
23    WRITE(1,1010) (ASHAPE(I),I=1,17)
      READ(1,*) SHAPE
      IF(SHAPE.NE.1.0.AND.SHAPE.NE.2.0.AND.SHAPE.NE.3.0
     $   .AND.SHAPE.NE.4.0) THEN
         WRITE(1,*)' PLEASE CHECK SHAPE NUMBER.'
         GO TO 23
      ENDIF


      IF (TYPE.EQ.2.0) THEN

         IF (SHAPE.EQ.1.0.OR.SHAPE.EQ.2.0) THEN
            WRITE(1,1103)
            GO TO 133
         ENDIF

      ENDIF


C     DIMENSIONS OF COLLECTOR:

      WRITE(1,*)' ENTER DIMENSIONS OF COLLECTOR.'
      WRITE(1,*)' LENGTH (ft) ?'
      READ(1,*) L1
      WRITE(1,*)' WIDTH (ft) ?'
      READ(1,*) L2
     WRITE(1,*)' HEIGTH (ft) ?'
      READ(1,*) L3

C     .....INPUT OPTICAL PROPERTIES AND COSTS OF COVER.....
```

```
      IF(TYPE.NE.3.0) THEN

         FNAME = 'COVER'
         CALL PRINTABLES(FNAME,8,5,8,6)

      ENDIF


C     .....INPUT THERMAL PROPERTIES AND COSTS OF INSULATION.....
      FNAME ='INSULATI'
      CALL PRINTABLES(FNAME,10,9,8,4)


C     .....INPUT OPTICAL PROPERTIES AND COSTS OF ABSORBER.....

      FNAME = 'ABSORB'
      CALL PRINTABLES(FNAME,10,3,9,7)

3     WRITE(1,*)' ENTER INITIAL MOISTURE CONTENT(WET BASIS).'
      WRITE(1,*) ' AS A PERCENTAGE.'
      READ(1,*) IMC
      WRITE(1,*)' ENTER FINAL MOISTURE CONTENT(WET BASIS).'
      WRITE(1,*)' AS A PERCENTAGE.'
      READ(1,*) FMC
      IF(FMC.GT.IMC.OR.FMC.LT.0.) THEN
         WRITE(1,*)' PLEASE CHECK YOUR DATA.'
         GO TO 3
      ELSEIF(IMC.GT.31.5) THEN
         WRITE(1,*)' YOUR INITIAL MOISTURE CONTENT IS TOO HIGH.'
         GO TO 3
      END IF
      WRITE(1,*)' HOW MANY BUSHELS OF CORN DO YOU PLAN ',
     $          'TO HARVEST PER YEAR ? '
      READ(1,*)TOTBU
      WRITE(1,*)' WHAT SIZE IS YOUR DRYING BIN ? (BUSHELS) '
      READ(1,*) VOLBIN
      WRITE(1,*)' WHAT IS THE CROSS SECTIONAL AREA OF ',
     $          'YOUR DRYING BIN ? (SQR.FT)'
      READ(1,*) ASTORAGE


C     PROCEDURE TO CALCULATE BUSHELS PER BATCH

      DEPTH = VOLBIN * 1.25 / ASTORAGE
      IF(DEPTH.GT.4.0) THEN

         DEPTH = 4.0

      ENDIF
```

```
      BU = ASTORAGE * DEPTH / 1.25
      IF(AMOD(TOTBU,BU).GT.1.0) THEN
         NBATCH = INT(TOTBU/BU) + 1
      ELSE
         NBATCH = INT(TOTBU/BU)
      ENDIF


C     .....READ START DATE OF DRYING.....

      CALL DAYNUM(DAY,IEXT,MN,LASTDM)

C          .....READ  IF  USER  WANTS  TO  SET  MAXIMUM  TIME  ALLOWED  TO
DRY                 THE PRODUCT....
      CALL TIMED1(DAYS1,FACTOR)


C     .....INPUT AIRFLOW RATE FOR THE SYSTEM.....

      CFM = 5.*BU
      CALL AIRFLOW(BU,CFM)

C     .....CALCULATE AREAS.....

      CALL AREA(SHAPE)
      RACOV = ACOV/AABS
      RABOT = ABOT/AABS
      ABSNO = AABS/NO

C     .....DETERMINATION OF AIR VARIABLES.....
      AIRVEL = CFM/ACROSS
      AIRMASS = ROAIR*CFM
      GCROSS = AIRMASS*60.

      IF(TYPE.EQ.2.0) THEN

         CALL SUSPENDED(SHAPE)

      ELSE

         DH = 4.*ACROSS / PER
         G = GCROSS / AABS
         RE = ROAIR*AIRVEL*DH*60. / MU

      ENDIF


C     .....VALUES OF ENERGY REQUIREMENTS PER HOUR FOR DRYING FAN.....

      COLLKW = FANCOLLE(CFM)
      GRAINKW = FANGRAINE(ASTORAGE,CFM,DEPTH)
```

```
C     .....ENTER INITIAL COST OF FAN, ASSUME USEFUL LIFE FOR FAN.....

      HPFAN = NINT(COLLKW + GRAINKW)/0.7457
      WRITE(1,1101) HPFAN
      READ(1,*) FANINI

C     .....INPUT AIR TEMPERATURE INCREASE AT NIGHT DUE TO HEATER.....
C     .....INPUT COST OF ELECTRICITY AND LPGAS.....

      CALL INPUTS1(DELTAT,ELCT,LPGAS)


C     .....ENTER INITIAL COST OF AIRHEATER. ASSUME USEFUL LIFE.....
C          (ASSUME 85% EFFICIENCY OF HEATER.)

      HEATERLPG = GCROSS*CP*DELTAT / 0.85
      WRITE(1,1102) HEATERLPG
      READ(1,*)HEATINI

C     .....ENTER INTEREST ON THE MONEY INVESTED.....

      WRITE(1,*) 'WHAT INTEREST ON THE MONEY INVESTED DO YOU USE? (%)'
      READ(1,*) INTEREST


C     .....CONVERSION OF IMC AND FMC FROM % TO DECIMAL.....

      IMCW = IMC/100.
      FMCWB = FMC/100.

C     .....CONVERSION OF MOISTURE CONTENT FROM W.B. TO D.B....

      IMCDB = WBTODB(IMCWB)
      FMCDB = WBTODB(FMCWB)


C     .....CALCULATE VALUES WHICH ARE CONSTANT FOR WHOLE SIMULATION.....

      CALL COLMATERIALS(SHAPE,SIGMA,TYPE)


C     .....INITIALIZE VARIABLES.....

C     .....TIME-KEEPERS.....
      ACCTIME = 0.
      TIMECOLL = 0.
      TIMEHEATER = 0.

C     ..... TOTAL USEFUL HEAT COLLECTED.....
      TOTQ = 0.
```

```
C      .....VALUES OF ENERGY PER UNIT OF TIME.....
       HEATERLPG = GCROSS*CP*DELTAT

C      .....VARIABLE USED TO PRINT PROCESSED DATA .....

       DPRN = DAY - 1.

C      .....PRINTING INITIAL VALUES ON "USERFILE".....

       CALL SUBOUT1(ASTORAGE,AW,BU,CITYNAME,DEPTH,DAY,FMCWB,G,
      $          IMCWB,LAT,LOLONG,MONTH(MN),SHAPE,SIGMA
      $          ,TYPE,TOTBU)

       WRITE(11,1111) TYPE,NO,CFM

C      .......BATCH LOOP.....

       DO 9999 LBATCH = 1,NBATCH

C      .....READ WEATHER DATA .....

       CALL READWEATHER(DAY,MN,LASTDM)

C              .....DETERMINE AVERAGE AMBIENT TEMPERATURE.....

          AVGTAMB = AVGTEMP(DAY)

C              .....CALCULATIONS   TO   DETERMINE   DECLINATION   ANGLE,
SUNRISE                  AND SUNSET.....

      IF(MN.EQ.12) THEN
         IF(DAY+15.GT.LASTDM) THEN
            DAYN = 365.
         ELSE
            DAYN = (FLOAT(JULIAN(1)) + FLOAT(JULIAN(10)))/2.
         ENDIF
      ELSE
         DAYN = (FLOAT(JULIAN(1)) + FLOAT(JULIAN(10)))/2.
      ENDIF

      DEC = DELTA(DAYN)

      LATRAD = LAT*RADDEG
      DECRAD = DEC*RADDEG
```

```
      FROMSRISE = HSR(LATRAD,DECRAD)*12./PI
       SRTIME = 12. - FROMSRISE
       SSTIME = 12. + FROMSRISE
       IDAWN = INT(SRTIME) + 1
       ISSET = INT(SSTIME)
       KDAWN = IDAWN + 2

C      .....INITIALIZE M.C. FOR DRYING MODEL.....

       AVGMC = IMCDB
       ACCEN = 0.

C      .....WRITE OUTPUT HEADINGS FOR BATCH PART ON USERFILE.....

          WRITE(16,1106) LBATCH,MONTH(MN),DAY
          WRITE(16,1107) SRTIME,SSTIME
          WRITE(16,1108) KDAWN,ISSET

C      .....DETERMINE TIME ALLOWED TO DRY CORN .....

          CALL DAYS(KDL,DAYS1,FACTOR,IMCWB,AVGTAMB)

C      .....PRINTING NAMES OF THE VARIABLES FOR PERFORMANCE OUTPUT.....

       WRITE(16,1104)
       WRITE(16,1105)

C      .....LOOP FOR DAILY CALCULATIONS.....

       DO 10000 KD = 1,KDL

C      .....PRINTING HEADINGS FOR TEMP.OUT FILE.....

       IF(TYPE.EQ.1.0) THEN
          WRITE(11,1112)MONTH(MN),DAY
       ELSEIF(TYPE.EQ.2.0) THEN
          WRITE(11,1113) MONTH(MN),DAY
       ELSE
          WRITE(11,1114) MONTH(MN),DAY
       ENDIF

C      .....SET DAILY VARIABLES EQUAL TO ZERO.....

       TIHOR = 0.
       TIDIR = 0.
       TIDIFF = 0.
```

```
      TDQUSEFUL = 0.
      AVGDT = 0.
      AVGDEFF = 0.
      AVGTOUT = 0.
      DQO = 0.


C     LOOP TO CALCULATE INCIDENT ANGLE, EFFECTIVE RADIATION, COLLECTOR
C     TEMPERATURE OUTPUT AND DRYING STATUS.

         DO 10001 HT = IDAWN+2,ISSET

C     .....THIS DO LOOP CALCULATES HOURLY:

C                    A. POSITION OF THE SUN:
C                    B. DIRECT AND DIFFUSE RADIATION INCIDENT
C                       ON THE COLLECTOR SURFACE:


C     .....ACCUMULATED TIME VALUES.....

      TIMECOLL = TIMECOLL + 1.
      ACCTIME = ACCTIME + 1.


C     .....CALCULATES INCIDENT ANGLE.....

            HS = (12. - HT) * PI/12.
            ALT = ASIN(COS(LATRAD)*COS(DECRAD)*COS(HS)+
     $           SIN(LATRAD)*SIN(DECRAD))
            A = ASIN((COS(DECRAD)*SIN(HS))/COS(ALT))
            IF((COS(HS)-TAN(DECRAD)/TAN(LATRAD)).GT.0.) THEN
               AZIM = A
            ELSE
               AZIM = PI - A
            ENDIF
            INCID = ACOS(COS(ALT)*COS(AZIM - AW)*SIN(SIGMARAD) +
     $                  SIN(ALT)*COS(SIGMARAD))


C     .....DETERMINATION OF DIRECT AND DIFFUSE RADIATION.....

            KT = QRAD(KD,HT)/(IEXT*SIN(ALT))
            KB1 = KB(KT)
            IB = KB1*IEXT
            ID = QRAD(KD,HT) - IB*SIN(ALT)
            IBT = IB*COS(INCID)
            IDT = 0.5*(1+COS(SIGMARAD))*ID + 0.5*(1 - COS(SIGMARAD))
     $         *ROGROUND*QRAD(KD,HT)
```

```
C     .....CALCULATES DEW-POINT TEMPERATURE, DEG. F.....

            RH =RHUM(KD,HT)/100.
            CALL DBRH(TEMP(KD,HT),RH,TDB,TDP)


C     .....CONVERSION  FROM RADIANS TO DEGREES.....

            DEGINCID = INCID*DEGRAD
            DEGHS = HS*DEGRAD
            DEGALT = ALT*DEGRAD
            DEGAZIM = AZIM*DEGRAD


C     .....CALCULATE TOTAL SOLAR RADIATION INCIDENT AND TRANSMITTED
C          THROUGH COLLECTOR SURFACE.....

            QO = IBT + IDT

          IF(TYPE.NE.3.0) THEN

            TAU1QO = TRANS(COVFUNCT,DEGINCID)*IBT + TRANS(COVFUNCT,60.)
     $                *IDT

          ENDIF


C     .....SIMULATE COLLECTOR PERFORMANCE.....

          CALL TEMPGENERATOR(TEMP(KD,HT),TYPE)
          CALL PERFORMANCE(TEMP(KD,HT),WIND(KD,HT),TYPE,SHAPE)

C               .....CONDITION   FOR   MODEL   TO   RUN   DRYING   ROUTINE,
TOUT>TEMP(KD,HT)...

       TOUT1 = TOUT - 459.69
       IF(TOUT1.LT.TEMP(KD,HT)) THEN

          TOUT1 = TEMP(KD,HT)
          QUSEFUL = 0.
          EFF = 0.

       ELSE

C     .....DRYING MODEL.....

          TO = TOUT + 2.
          TO = TO-459.69
          CALL DRYING(ACCTIME,ASTORAGE,CFM,DEPTH,
     $          TDP,TO,TEMP(KD,HT),RHUM(KD,HT))
```

```
      ENDIF


C     .....CALCULATE DAILY VALUES.....

      TIHOR = TIHOR + QRAD(KD,HT)
      TIDIR = TIDIR + IBT
      TIDIFF =TIDIFF + IDT
      TDQUSEFUL = TDQUSEFUL + QUSEFUL
      AVGDEFF = AVGDEFF + QO*EFF
      DQO = DQO + QO
      TOUT1 = TOUT - 459.69
      AVGDT = AVGDT + (TOUT1 - TEMP(KD,HT))
      AVGTOUT = AVGTOUT + TOUT1

     .....PRINTING RESULTS ON FILE TEMP.OUT.....

         IF(TYPE.EQ.1.0) THEN
            WRITE(11,1115)HT,QRAD(KD,HT),WIND(KD,HT),TEMP(KD,HT),
     $                    T1,T2,TOUT1
         ELSEIF(TYPE.EQ.2.0) THEN
            WRITE(11,1116)HT,QRAD(KD,HT),WIND(KD,HT),TEMP(KD,HT),
     $                    T1,T2,T3,TOUT1
         ELSE
            WRITE(11,1115)HT,QRAD(KD,HT),WIND(KD,HT),TEMP(KD,HT),
     $                    T1,T2,TOUT1
         ENDIF


         IF(AVGMC.LT.FMCDB) THEN

           TOTQ = TOTQ + TDQUSEFUL
           TDQUSEFUL = TDQUSEFUL/1000.

      IF(INT(HT).EQ.KDAWN) THEN

         AVGDT = AVGDT
         AVGTOUT = AVGTOUT

      ELSE

         AVGDT = AVGDT/(HT - KDAWN)
         AVGTOUT = AVGTOUT/(HT - KDAWN)

      ENDIF

            AVGDEFF = AVGDEFF / DQO
            WRITE(16,1100) KD,TIHOR,TIDIR,TIDIFF,TDQUSEFUL,
     $                     AVGDEFF,AVGDT,AVGTOUT
            WRITE(16,1109) KD,HT
```

```
            GO TO 9998

         ENDIF

10001    CONTINUE

C      .....CALCULATE DAILY VALUES FOR COLLECTOR PERFORMANCE.....

       TOTQ = TOTQ + TDQUSEFUL
       TDQUSEFUL = TDQUSEFUL/1000.
       AVGDT = AVGDT/(HT - KDAWN)
       AVGDEFF = AVGDEFF/DQO
       AVGTOUT = AVGTOUT/(HT - KDAWN)
       WRITE(16,1100) KD,TIHOR,TIDIR,TIDIFF,TDQUSEFUL,AVGDEFF,
      $               AVGDT,AVGTOUT

       DO 10002 HT = ISSET+1,24

          ACCTIME = ACCTIME + 1.
          TIMEHEATER = TIMEHEATER + 1.

          RH = RHUM(KD,HT)/100.
          CALL DBRH(TEMP(KD,HT),RH,TDB,TDP)

          TO = DELTAT + TEMP(KD,HT) + 2.

          CALL DRYING(ACCTIME,ASTORAGE,CFM,DEPTH,
      $               TDP,TO,TEMP(KD,HT),RHUM(KD,HT))

10002  CONTINUE


       DO 10003 HT = 1,IDAWN-1

          ACCTIME = ACCTIME + 1.
          TIMEHEATER = TIMEHEATER + 1.

          RH = RHUM(KD,HT)/100.
          CALL DBRH(TEMP(KD,HT),RH,TDB,TDP)

          TO = DELTAT + TEMP(KD,HT) + 2.

          CALL DRYING(ACCTIME,ASTORAGE,CFM,DEPTH,
      $               TDP,TO,TEMP(KD,HT),RHUM(KD,HT))

10003  CONTINUE
C      .....END DO LOOP FOR HOURLY CALCULATIONS.....

          IF(AVGMC.LT.FMCDB) THEN

             KD1 = KD + 1
```

```
            WRITE(16,1109)KD1,HT
            GO TO 9998

         ENDIF


C     .....END DO LOOP FOR DAILY CALCULATIONS.....


10000 CONTINUE

C     .....END DO LOOP FOR DAILY CALCULATIONS.....

9998  AVMCWB = DBTOWB(AVGMC)
      WRITE(16,1110) AVMCWB

      DAY = DAY + KD

      IF(DAY.GT.LASTDM) THEN

         IF(MN.EQ.12) THEN
            MN = 1
         ELSE
            MN = MN + 1
         ENDIF

         DAY = DAY - LASTDM

      ENDIF

      CALL DATE(IEXT,LASTDM,MN)

9999  CONTINUE


C     .....ENERGY CALCULATIONS FOR FAN.....

      TFANCOLLE = TIMECOLL*COLLKW
      TFANGRAINE = ACCTIME*GRAINKW
      TEFAN = TFANCOLLE + TFANGRAINE
      TFANECOST = ELCT*TEFAN

C     .....ENERGY CALCULATIONS FOR HEATER.....

     TOTLPE = TIMEHEATER * HEATERLPG/1.0E6
      TOTLPGAS = TOTLPE/0.1016
      TCEHEAT = TOTLPGAS*LPGAS

C     .....CALCULATE TOTAL USEFUL ENERGY.....

      LPGSAV = TOTQ/101.6E3
```

```
      AESAV = LPGSAV * LPGAS

      CALL ECANALYSIS(BU,INTEREST,NBATCH,TYPE)

      CALL SUBOUT2(DELTAT,ELCT,INTEREST,LPGAS,
     $      TOTQ,TOTLPE,AESAV)

      CLOSE(11)
      CLOSE(12)
      CLOSE(16)

30    FORMAT(A20)
1000  FORMAT(A10)
1010  FORMAT(A72)
10    FORMAT(T10,F6.2,T20,F6.2,T30,F6.2,T40,F6.2,T50,F6.2,T60,F6.2)
11    FORMAT(5(/),22X,'OUT PUT DATA FROM SUNPATH SIMULATION')
12    FORMAT(///,10X,'MONTH:',A10/10X,'DAY: ',F3.0/10X,'SUNRISE AT:',
     $       F6.2,' HOURS.'/10X,'SUNSET AT:',F6.2,' HOURS.')
1050    FORMAT(///,9X,'STANDARD',3X,'SOLAR',6X,'HOUR',4X,'ALTITUDE',2X,
     $        'AZIMUTH',2X,'INCIDENT'/11X,'TIME',6X,'TIME',5X,'ANGLE',
     $        5X,'ANGLE',5X,'ANGLE',4X,'ANGLE'/10X,'HOURS',5X,'HOURS',
     $        4(6X,'DEG.')///)
1100  FORMAT(2X,F3.0,4X,F7.2,2X,F7.2,2X,F7.2,3X,F8.2,4X,
     $         F4.2,6X,F4.1,4X,F5.1)
1101  FORMAT(3X,'ENTER THE INITIAL COST OF THE FAN. THE FAN SIZE',
     $        ' REQUIRED IS'/3X,'APPROXIMATELY ',I3,' HP.')
1102  FORMAT(3X,'ENTER THE INITIAL COST OF THE HEATER. THE SIZE',
     $        ' REQUIRED '/3X,'IS APPROXIMATELY ',F8.0,' BTU/HR.')
1103  FORMAT(10(/),5X,'THIS MODEL CAN ANALYZE ONLY RECTANGULAR ',
     $      'AND SEMICIRCULAR CROSS ',//5X,'SECTIONAL SHAPES FOR ',
     $      'SUSPENDED PLATE COLLECTORS.'///5X,'PLEASE REENTER THE TYPE'
     $     ,' AND SHAPE OF THE COLLECTOR YOU WANT.',10(/))

1104  FORMAT(7(/),T19,'DAILY INFORMATION ON COLLECTOR PERFORMANCE')
1105  FORMAT(3X,'DAY',4X,'TOTAL',4X,'TOTAL',4X,'TOTAL',5X,'TOTAL',
     $       4X,'AVERAGE',3X,'AVERAGE',3X,'AVERAGE'/10X,'HOR.',5X,
     $       'DIR.',5X,'DIFF.',4X,'USEFUL',4X,'THERMAL',4X,'TEMP.',
     $       4X,'OUTLET'/10X,'RAD.',5X,'RAD.',5X,'RAD.',6X,'HEAT',
     $       7X,'EFF.',4X,'INCREASE',3X,'TEMP.'/9X,'Btu/ft2',2X,
     $       'Btu/ft2',2X,'Btu/ft2',3X,'Btu/1000',4X,'dec.',7X,
     $         'F',8X,'F'//)
1106  FORMAT(4(/),2X,'STARTING DATE FOR BATCH ',I2,1X,A10,1X,F3.0//)
1107  FORMAT(2X,'SUNRISE AT ',F5.2,' HOURS (SOLAR TIME)'/2X,
     $         'SUNSET AT ',F5.2,' HOURS (SOLAR TIME)')
1108  FORMAT(2X,'THE COLLECTOR OPERATES FROM ',I2,' TO ',I2,' HOURS')
1109  FORMAT(//5X,'BATCH IS DRY ON DAY NUMBER ',
     $        I2,' AT ',I2,' HOURS.')
1110  FORMAT(//5X,'FINAL AVERAGE MOISTURE CONTENT (WET BASIS) IS ',
     $       F5.2)
```

```
1111  FORMAT(5X,'COLLECTOR TYPE ',F3.0/5X,'NUMBER OF SEGMENTS '
     $    ,I2/5X,'AIRFLOW RATE ',F7.0,' CFM')
1112  FORMAT(4(/),5X,'DATE : MONTH : ',A10/12X,'DAY : ',F3.0//
     $   5X,'TIME  TOTAL',7X,'WIND',5X,'TAMB',5X,'TCOVER',3X,'TABS',
     $   5X,'TOUT'/11X,'HOR.RAD.',4X,'SPEED',4X,'IENT',14X,'ORBER'/
     $   6X,'HR',3X,'Btu/ft2-HR',3X,'MPH',6X,'F',10X,'F',7X,'F',8X,'F')
1113  FORMAT(4(/),5X,'DATE : MONTH: ',A10/12X,'DAY : ',F3.0//
     $   5X,'TIME  TOTAL',7X,'WIND',5X,'TAMB',5X,'TCOVER',3X,'TABS',
     $   5X,'TBOT',5X,'TOUT'/11X,'HOR.RAD.',4X,'SPEED',4X,'IENT',14X,
     $   'ORBER',4X,'TOM'/6X,'HR',3X,'Btu/ft2-HR',3X,'MPH',
     $   6X,'F',10X,'F',7X,'F',8X,'F',8X,'F')
1114  FORMAT(4(/),5X,'DATE : MONTH : ',A10/12X,'DAY : ',F3.0//5X,
                                        $                    'TIME
TOTAL',7X,'WIND',5X,'TAMB',5X,'TABS',5X,'TBOT',5X,'TOUT'/
     $   11X,'HOR.RAD.',4X,'SPEED',4X,'IENT',5X,'ORBER',4X,'TOM'/6X,
     $   'HR',3X,'Btu/ft2-HR',3X,'MPH',6X,'F',9X,'F',8X,'F',8X,'F')
1115  FORMAT(6X,I2,3X,F6.2,5X,F6.2,3X,F5.1,5X,F5.1,4X,F5.1,3X,F5.1)
1116  FORMAT(6X,I2,3X,F6.2,5X,F6.2,3X,F5.1,5X,F5.1,4X,F5.1,3X,F5.1,
     $           5X,F5.1)

      STOP
      END


C-----------------------------------------------------------------
      SUBROUTINE AIRFLOW (BU,CFM)
C-----------------------------------------------------------------

C     THIS ROUTINE CHECKS IF THE USER WANTS TO INPUT THE AIRFLOW RATE.

      CHARACTER*1 ANS

      CFMBU = 5.0
      WRITE(1,10)CFMBU
      WRITE(1,11)CFM
      WRITE(1,12)
      READ(1,9)ANS

      IF(ANS.EQ.'Y') THEN

         WRITE(1,13)
         READ(1,*)CFMBU
         CFM = CFMBU*BU

      ENDIF

9     FORMAT(A1)
10    FORMAT(6(/)7X,'THE DEFAULT VALUE FOR AIRFLOW RATE'
     $   ,' USED IN THIS MODEL'//7X,'IS ',F5.2,' CFM/BU.')
11    FORMAT(//7X,'BASED ON THIS VALUE THE AIRFLOW RATE FOR THIS'//
     $       7X,'SYSTEM WOULD BE ',F8.2,' CFM.')
```

```
12    FORMAT(4(/),7X,'DO YOU WANT TO CHANGE THE AIRFLOW RATE'
     $       ,' ? (Y/N)')
13    FORMAT(4(/)7X,'PLEASE ENTER THE AIRFLOW RATE PER BUSHEL '
     $       ,'(CFM/BU)'//)

      RETURN
      END

C-----------------------------------------------------------------
      REAL*4 FUNCTION ANUAL(P,I,N)
C-----------------------------------------------------------------

C      THIS FUNCTION CALCULATES THE ANUAL EQUIVALENT COST OF THE SOLAR
SYSTEM.

      REAL*4 I,N

      IF(P.EQ.0.0) THEN

        ANUAL = 0.

      ELSE

         ANUAL = P * (I * (1. + I)**N/((1. + I)**N - 1.))

      ENDIF

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE AREA(SHAPE)
C-----------------------------------------------------------------

      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/DIMENSIONS/NO,L1,L2,L3

      REAL*4 L1,L2,L3

      IF (SHAPE.EQ.1) THEN

         X3 = SQRT(L2**2 + L3**2)
         AABS = L1 * X3
         EDGE = 0.5*L3
         ASIDES = 2. * EDGE * L1
         AENDS = L2 * L3
         PER = L2 + L3 + X3
         ACROSS = 0.5 * L2 * L3
         ACOV = L1 * X3
```

```
      ELSEIF (SHAPE.EQ.2) THEN

         AABS = L1 * L2
         EDGE = 0.333
         ASIDES = 2. * EDGE * L1
         AENDS = L2 * L3
         X1 = L2/2.
         X3 = SQRT(X1**2 + L3**2)
         PER = 2 * (X1 + X3)
         ACROSS = 0.5 * L3 * L2
         ACOV = 2 * L1 * X3

      ELSEIF (SHAPE.EQ.3) THEN

         AABS = L2 * L1
         EDGE = L3
         ASIDES = 2. * EDGE * L1
         AENDS = 2. * L2 * L3
         PER = 2 * (L2+L3)
         ACROSS = L2*L3
         ACOV = AABS

      ELSE

         PI = ACOS(-1.)
         AABS = L1 * L2
         EDGE = 0.
         ASIDES = 0.
         AEND = 2. * 3.33 * 8.5 * 0.5
         AENDS = 2. * AEND
         RADIUS = L2**2/(8.*L3) + L3/2.
         TETA = ASIN((RADIUS - L3)/RADIUS)
         A1 = RADIUS**2 * TETA/2
         A2 = L2/2 * (RADIUS-L3)*0.5
         A12 = 2 * (A1 + A2)
         ACROSS = PI * RADIUS**2 *0.5 - A12
         PER = L2 + RADIUS*(PI - 2*TETA)
         ACOV = L1 * (PER - L2)

      ENDIF

      AEDGE = ASIDES + AENDS
      ABOT = AABS + AEDGE

      RETURN
      END


C-----------------------------------------------------------------------
      REAL*4 FUNCTION AVGTEMP(DAY)
C-----------------------------------------------------------------------
```

```
      COMMON/WEATHER/JULIAN(31),TIME(31,24),WIND(31,24),
     $               QRAD(31,24),RHUM(31,24),TEMP(31,24)

      SUMTEMP = 0.

      DO 10 K = 1, 10

         DO 10 KH = 1,24
            SUMTEMP = SUMTEMP + TEMP(K,KH)
10    CONTINUE

      AVGTEMP = SUMTEMP/240.

      RETURN
      END


C-----------------------------------------------------------------
      REAL*4 FUNCTION BPVWB(PV,WB)
C-----------------------------------------------------------------

      COMMON/ATMPRES/PATM

      BPVWB=0.2405*(PSDB(WB)-PATM)*(1.0+0.15577*PV/PATM)/.62194/HLDB(WB)

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE COLMATERIALS(SHAPE,SIGMA,TYPE)
C-----------------------------------------------------------------

      COMMON/ABSMATERIAL/ABSABS,ABSANU,ABSEMIS,ABSINI,ABSINS,
     $       ABSMAT,ABSYRS
      COMMON/COVMATERIAL/COVANU,COVEMIS,COVFUNCT,COVINIT,COVINS,
     $       COV1MAT,COV2MAT,COVTL,COVTS,COVYRS
      COMMON/INSMATERIAL/INSANU,INSINI,INSINS,INSMAT,INSRIN,
     $       INSTHIK,INSYRS
      COMMON/MATCOLT/A1S,A2S,A3S,E1L,E2L,E12L,E23L,
     $       RBOTTOM,RO1S,RO12S,TAULONG,TAUSHORT

      CHARACTER*18 ABSMAT
      CHARACTER*18 COV1MAT,COV2MAT
      CHARACTER*6 COVFUNCT
      CHARACTER*18 INSMAT

      REAL*4 INSANU,INSINI,INSINS,INSRIN,INSTHIK,INSYRS
      REAL*4 HBOTTOM
```

```
      HBOTTOM = 0.37

      IF(TYPE.EQ.3.0) THEN

         A1S = ABSABS / 100.
         E1L = ABSEMIS / 100.
         E2L = E1L
         RBOTTOM = INSRIN*INSTHIK + 1./HBOTTOM

      ELSE

         TAULONG = COVTL/100.
         TAUSHORT = COVTS/100.
C        E1L = (1. - TAU1L)/2.0
         E1L = 0.1

         A2S = ABSABS/100.
         E2L = ABSEMIS/100.

         A1S = (1.0 - TAUSHORT) / 2.0
         R01S = A1S

         R02S = 1. - A2S

         R012S = R02S / (1.0 - R01S*R02S)

         IF(SHAPE.EQ.4.0.AND.SIGMA.EQ.0.0) THEN

            RBOTTOM = 100.

         ELSE

            RBOTTOM = INSRIN*INSTHIK + 1/HBOTTOM

         ENDIF

      ENDIF

      IF(TYPE.EQ.1.0) THEN

         E12L = (E1L*E2L) / (1. - (1.-TAU1L - E1L) * (1.-E2L))

      ELSEIF(TYPE.EQ.2.0) THEN

         E3L = E2L
         E12L = (E1L*E2L) / (1. - (1.-TAU1L-E1L) * (1.-E2L))
         E23L = 1. / (1./E2L + 1./E3L - 1.)

      ELSE

         E12L = 1.0 / (1.0/E1L + 1.0/E2L - 1.0)
```

```
      ENDIF

      RETURN
      END

C-----------------------------------------------------------------
      SUBROUTINE COLT1(TAMB,F)
C-----------------------------------------------------------------

C     AABS,ACOV,ACROSS: AREAS OF ABSORBER,COVER AND CROSS SECTIONAL
C                       AREA OF COLLECTOR.
C     DH: EQUIVALENT RADIUS.
C     TAMB: AMBIENT TEMPERATURE, DEG.F.
C     RAD: RADIATION INCIDENT OVER SURFACE OF COLLECTOR,BTU/(SQR.FT-HR.)
C     AIRVEL: VELOCITY OF THE AIR THROUGHTOUT COLLECTOR, FT./MIN.
C     T(I): TEMPERATURE OF COVER AND ABSORBER, DEG.R.
C     H(I): CONVECTION FILM COEFFICIENT, BTU/(SQR.FT-DEG.F.)
C     F(I): EQUATIONS 1 AND 2.
C     DF(I): DERIVATIVES OF EQUATIONS 1 AND 2.
C     SIGMA: STEFAN-BOLTZMANN CONSTANT, BTU/SQR.FT-(DEG.R.)**4.


      COMMON/MATCOLT/A1S,A2S,A3S,E1L,E2L,E12L,E23L,
     $       RBOTTOM,RO1S,RO12S,TAULONG,TAUSHORT
      COMMON/AIRPROPERTIES/CP,K,MU,ROAIR
      COMMON/AIRVARIABLES/ AIRMASS,AIRVEL,CFM
      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/PERFVAR/HW,QO,TAU1QO,TSKY
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2
      COMMON/TEMPERATURES/T1,T2,T3,TF,TF1,TF2
      COMMON/PARTDER/DF(3,3)

      REAL*4 F(3)
      REAL*4 H1,H2,MU

C     .....CONSTANTS.....
      SIGMA = 0.1714E-08

C     .....CALCULATIONS OF COEFF. OF FUNCTIONS AND THEIR DERIV. .....

      A11 = SIGMA*(E1L *RACOV + E12L)
      A12 = (-SIGMA)*E12L

      B11 = RACOV*(HW + H1*(1. - RACOV*H1/DEN))
      B12 = (-1)*(RACOV*H1*H2 / DEN)
```

```
      C1 = (-1.)*RACOV*(((H1 * 2.*GCROSS*CP*TIN / ABSNO)
     $       / DEN)
     $     + (QO + TAU1QO*RO12S)*A1S
     $     + HW*TAMB + SIGMA*E1L*TSKY**4.)

      A21 = SIGMA * E12L
      A22 = (-SIGMA)*(E12L + E2L * TAULONG)

      B21 = RACOV*H1*H2 / DEN
      B22 = (-1)*((RABOT/RBOTTOM) + H2*(1 - H2/DEN))

      C2 = (2.*GCROSS*CP*H2*TIN / ABSNO)/ DEN
     $       + A2S*TAU1QO*(1 + RO1S*RO12S)
     $       + TAMB*RABOT/RBOTTOM
     $       + SIGMA*E2L*TAULONG*TSKY**4.

C     .....CALCULATION OF THE FUNCTIONS.....

      F(1) = A11*T1**4 + A12*T2**4 + B11*T1 + B12*T2 + C1
      F(2) = A21*T1**4 + A22*T2**4 + B21*T1 + B22*T2 + C2

      WRITE(14,112)F(1),F(2)
112   FORMAT(//3X,'F1 = ',E12.5,3X,'F2 = ',E12.5)

C     .....CALCULATION OF THE PARTIAL DERIVATIVES OF F(1) AND F(2).....

      DF(1,1) = 4*A11*T1**3 + B11
      DF(1,2) = 4*A12*T2**3 + B12
      DF(2,1) = 4*A21*T1**3 + B21
      DF(2,2) = 4*A22*T2**3 + B22

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE COLT2(TAMB,F)
C-----------------------------------------------------------------------

      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/MATCOLT/A1S,A2S,A3S,E1L,E2L,E12L,E23L,
     $       RBOTTOM,RO1S,RO12S,TAULONG,TAUSHORT
      COMMON/AIRVARIABLES/AIRMASS,AIRVEL,CFM
      COMMON/AIRPROPERTIES/CP,K,MU,ROAIR
      COMMON/PERFVAR/HW,QO,TAU1QO,TSKY
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2
      COMMON/TEMPERATURES/T1,T2,T3,TF,TF1,TF2
      COMMON/PARTDER/DF(3,3)
```

```
      DIMENSION F(3)

C     .....CONSTANT.....
      SIGMA = 0.1714E-08

      A11 = SIGMA * (RACOV*E1L + E12L)
      A12 = (- SIGMA) * E12L
      A13 = 0.

      B11 = RACOV * (H1 + HW - RACOV*H1**2/DEN1)
      B12 = (-RACOV) * H1*H2P/DEN1
      B13 = 0.

      C1 = (-RACOV) * (A1S * (QO + RO12S*TAU1QO)
     $     + HW*TAMB + SIGMA*E1L*TSKY**4
     $     + H1 * ((2.*G1*CP*TIN1/ABSNO) / DEN1))

      A21 = SIGMA*E12L
      A22 = (-SIGMA) * (E12L + E23L + TAULONG*E2L)
      A23 = SIGMA * E23L

      B21 = RACOV * H1 * H2P / DEN1
      B22 = (-1.) * (H2P + H2PP - H2P**2/DEN1
     $      - H2PP**2/DEN2)
      B23 = RABOT * H2PP * H3/DEN2

      C2 = A2S * TAU1QO * (1. + RO1S*RO12S)
     $     + SIGMA*TAULONG*E2L*TSKY**4
     $     + (H2P*2.*G1*CP*TIN1/ABSNO) / DEN1
     $     + (H2PP*2*G2*CP*TIN2 / ABSNO) / DEN2

      A31 = 0.
      A32 = SIGMA * E23L
      A33 = (-SIGMA) * E23L

      B31 = 0.
      B32 = RABOT*H2PP*H3/DEN2
      B33 = (-RABOT) * (H3 + (1/RBOTTOM)
     $      - RABOT*H3**2/DEN2)

      C3 = RABOT * (TAMB/RBOTTOM + (H3*2*G2*CP*TIN2/ABSNO) / DEN2)

      F(1) = A11*T1**4 + A12*T2**4 + A13*T3**4
     $       + B11*T1 + B12*T2 + B13*T3 + C1
      (2) = A21*T1**4 + A22*T2**4 + A23*T3**4
     $       + B21*T1 + B22*T2 + B23*T3 + C2
      F(3) = A31*T1**4 + A32*T2**4 + A33*T3**4
     $       + B31*T1 + B32*T2 + B33*T3 + C3

      DF(1,1) = 4*A11*T1**3 + B11
      DF(1,2) = 4*A12*T2**3 + B12
```

```
      DF(1,3) = 4*A13*T3**3 + B13

      DF(2,1) = 4*A21*T1**3 + B21
      DF(2,2) = 4*A22*T2**3 + B22
      DF(2,3) = 4*A23*T3**3 + B23

      DF(3,1) = 4*A31*T1**3 + B31
      DF(3,2) = 4*A32*T2**3 + B32
      DF(3,3) = 4*A33*T3**3 + B33

      WRITE(10,211)F(1),F(2),F(3),((DF(I,J),J=1,3),I=1,3)
211   FORMAT(12(1X,E10.4))

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE COLT3(TAMB,F)
C-----------------------------------------------------------------

      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/MATCOLT/A1S,A2S,A3S,E1L,E2L,E12L,E23L,
     $       RBOTTOM,RO1S,RO12S,TAULONG,TAUSHORT
      COMMON/AIRVARIABLES/AIRMASS,AIRVEL,CFM
      COMMON/AIRPROPERTIES/CP,K,MU,ROAIR
      COMMON/PERFVAR/HW,QO,TAU1QO,TSKY
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $      TIN,TIN1,TIN2
      COMMON/TEMPERATURES/T1,T2,T3,TF,TF1,TF2
      COMMON/PARTDER/DF(3,3)

      DIMENSION F(2)

      A11 = SIGMA * (E1L + E12L)
      A12 = (-SIGMA) * E12L

      B11 = H1 + HW - (H1**2)/DEN
      B12 = (-1.) * (RABOT * H1 * H2 / DEN)

      C1 = (-A1S)*QO - HW*TAMB - SIGMA*E1L*TSKY**4
     $     - (H1*2.*GCROSS*CP*TIN / ABSNO) / DEN

      A21 = SIGMA * E12L
      A22 = (-SIGMA) * E12L

      B21 = RABOT * H1 * H2 / DEN
      B22 = (-RABOT) * (H2 + (1/RBOTTOM) - (RABOT*H2**2) / DEN)
```

```
      C2 = RABOT * ((2*GCROSS*CP*H2*TIN / ABSNO) /DEN
     $     + TAMB / RBOTTOM)


      F(1) = A11*T1**4 + A12*T2**4 + B11*T1 + B12*T2 + C1
      F(2) = A21*T1**4 + A22*T2**4 + B21*T1 + B22*T2 + C2


     DF(1,1) = 4*A11*T1**3 + B11
      DF(1,2) = 4*A12*T2**3 + B12

      DF(2,1) = 4*A21*T1**3 + B21
      DF(2,2) = 4*A22*T2**3 + B22

           WRITE(14,111)A11,A12,B11,B12,C1,A21,A22,B21,B22,C2
111   FORMAT(5(3X,E12.5))
      WRITE(14,112)F(1),F(2)
112   FORMAT(//3X,'F1 = ',E12.5,3X,'F2 = ',E12.5)

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE CONVECT1(ISEG)
C-----------------------------------------------------------------------

      COMMON/AIRVARIABLES/AIRMASS,AIRVEL,CFM
      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/AIRPROPERTIES/CP,K,MU,ROAIR
      COMMON/DIMENSIONS/NO,L1,L2,L3
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2

      REAL*4 K,MU
      REAL*4 L1,L2,L3
      REAL*4 L
      REAL*4 H1,H2


C     .....PRANDTL NUMBER FOR THE AIR.....
      PR = 0.7

      L = L1*FLOAT(ISEG/NO)

      IF(L1.LT.1.0) THEN

         DH = 4.* ACROSS / PER
         RE = ROAIR*AIRVEL*DH*60. / MU
         NUINF = 0.0023*RE**0.8 * PR**0.4
```

```
         NULOCAL = (1.78 - 0.0864*(L/DH)**0.53)*NINF
         H1 = NULOCAL*K/DH
         H2 = H1

      ELSE

         H1 = 1 + 0.0034*AIRVEL
         H2 = H1

      ENDIF

      DEN = 2.*GCROSS*CP/ABSNO + RACOV*H1 + H2

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE CONVECT2 (ISEG)
C-----------------------------------------------------------------

C     THE PURPOSE OF THIS ROUTINE IS TO CALCULATE THE FILM CONVECTION
C     COEFFICIENTS FOR COLLECTOR TYPE II. H1, H2P, H2PP AND H3 ARE
C     CALCULATED BY USING THE FOLLOWING EQUATIONS:

C          1. NU = C*RE**M * PR**N, HOLMAN, P.61, EQ. FOR FULLY
C             DEVELOPED FLOW  IN SMOOTH TUBES.
C          2. NULOCAL = NU * (1.78 - 0.0864*(L/DH)**0.53) FROM TAN AND
C             CHARTERS, 1969.
C          3. NU = NU * ((1 - ((T2-TIN)/(T1-TIN)) * TETA)/(1-TETA**2)
C             AND
C             NU = NU * ((1 - ((T1-TIN)/(T2-TIN)) * TETA)/(1-TETA**2)
C             FROM KAYS, 1966, P.114,180 AND FITZGIBBONS AND KLINE,
C             1978 P.16.


      COMMON/AIRVARIABLES/AIRMASS,AIRVEL,CFM
      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/AIRPROPERTIES/CP,K,MU,ROAIR
      COMMON/DIMENSIONS/NO,L1,L2,L3
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2
      COMMON/TEMPERATURES/T1,T2,T3,TF,TF1,TF2

      REAL*4 NU1,NU2,NUINF1,NUINF2,NU11LOCAL,NU12LOCAL,
     $       NU22LOCAL,NU23LOCAL
      REAL*4 K,MU
      REAL*4 H1,H2P,H2PP,H3
      REAL*4 L
      REAL*4 L1,L2,L3
```

```
C     .....ASSUMED CONSTANT PR FOR AIR.....
      PR = 0.7

      L = L1*FLOAT(ISEG)/FLOAT(NO)

      NUINF1 = 0.023*RE1**0.8 * PR**0.4
      NU11LOCAL = NUINF1 * (1.78 - 0.0864*(L/DH1)**0.53)
      H1 = NU11LOCAL * K / DH1
      H2P = H1

      TETA2 = 0.57*RE2**(-0.106)
      NUINF2 = 0.023 * RE2**0.8 * PR**0.4
      NU2 = NUINF2*((1+((T3-TIN2)/(T2-TIN2)) * TETA2) / (1.-TETA2**2))
      NU23LOCAL = NU2 * (1.78 - 0.0864*(L/DH2)**0.53)
      H2PP = NU23LOCAL * K / DH2

      NU3 = NUINF2*((1+((T2-TIN2) / (T3-TIN2)) * TETA2) / (1-TETA2**2))
      NU3LOCAL = NU3 * (1.78 - 0.0864*(L/DH2)**0.53)
      H3 = NU23LOCAL * K / DH2

      DEN1 = 2.*G1*CP / ABSNO + H2P + RACOV*H1
      DEN2 = 2.*G2*CP / ABSNO + H2PP + RABOT*H3

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE CONVECT3(ISEG)
C-----------------------------------------------------------------------

      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/AIRPROPERTIES/CP,K,MU,ROAIR
      COMMON/DIMENSIONS/NO,L1,L2,L3
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2
      COMMON/TEMPERATURES/T1,T2,T3,TF,TF1,TF2

      REAL*4 K,MU
      REAL*4 L
      REAL*4 L1,L2,L3
      REAL*4 H1,H2
      REAL*4 NUINF,NU1,NU2,NU1LOCAL,NU2LOCAL


      PR = 0.7

      L = L1 * FLOAT(ISEG) / FLOAT(NO)
```

```
      TETA = 0.57 * RE**(-0.106)

      NUINF = 0.023 * RE**0.8 * PR**0.4


      NU1 = NUINF * ((1 + ((T2-TIN)/(T1-TIN)) * TETA) / (1-TETA**2))
      NU2 = NUINF * ((1 + ((T1-TIN)/(T2-TIN)) * TETA) / (1-TETA**2))


      NU1LOCAL = NU1 * (1.78 - 0.0864*(L/DH)**0.53)
      NU2LOCAL = NU2 * (1.78 - 0.0864*(L/DH)**0.53)

     H1 = NU1LOCAL * K / DH
      H2 = NU2LOCAL * K / DH


      DEN = (2 * GCROSS * CP / ABSNO) + H1 + RABOT*H2


      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE CORNDEPTH(ASTORAGE,BU,DEPTH,IMC,WEIGHT)
C-----------------------------------------------------------------

C     THE PURPOSE OF THIS ROUTINE IS TO DETERMINE THE VOLUME AND DEPTH
C     OF THE CORN TO BE DRIED.


      REAL*4 IMC
C
      Y = 47.50455 + IMC*(2.690727 - IMC*(0.1959915 - IMC*(0.0037441)))
      WEIGHT = BU*Y
      DEPTH = BU*1.25/ASTORAGE
      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE DATE(IEXT,LASTDM,MN)
C-----------------------------------------------------------------

      REAL*4 IEXT

      IF(MN.GT.12) THEN

         MN = 1
         LASTDM = 31
```

```
      IEXT = 447.06

   ELSEIF(MN.EQ.2) THEN

      LASTDM = 28
      IEXT = 443.89

   ELSEIF(MN.EQ.3) THEN

      LASTDM = 31
      IEXT = 437.55

   ELSEIF(MN.EQ.4) THEN

      LASTDM = 30
      IEXT = 431.21

   ELSEIF(MN.EQ.5) THEN

      LASTDM = 31
      IEXT = 424.87

   ELSEIF(MN.EQ.6) THEN

      LASTDM = 30
      IEXT = 421.70

   ELSEIF(MN.EQ.7) THEN

      LASTDM = 31
      IEXT = 421.70

   ELSEIF(MN.EQ.8) THEN

      LASTDM = 31
      IEXT = 424.87

   ELSEIF(MN.EQ.9) THEN

      LASTDM = 30
      IEXT = 431.21

   ELSEIF(MN.EQ.10) THEN

      LASTDM = 31
      IEXT = 437.55

   ELSEIF(MN.EQ.11) THEN

      LASTDM = 30
      IEXT = 443.89
```

```
      ELSE

         LASTDM = 31
         IEXT = 447.06

      ENDIF

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE DAYNUM(DAY,IEXT,MN,LASTDM)
C-----------------------------------------------------------------

      REAL*4 IEXT
      CHARACTER*10 MONTH

10    FORMAT(A10)
11    FORMAT(///,3X,'INPUT MONTH:')
12    FORMAT(///,3X,'INPUT DAY:')
13    FORMAT(///,20X,'PLEASE CHECK YOUR DATA AND INPUT IT AGAIN.')
14    FORMAT(14(/),20X,'INPUT THE DATE YOU WANT TO START DRYING.')

100   WRITE(1,14)
      WRITE(1,11)
      READ(1,10) MONTH

      WRITE(1,12)
      READ(1,*) DAY

      IF (DAY.GT.31.) GO TO 99

        IF(MONTH.EQ.'JANUARY') THEN

            MN = 1
            LASTDM = 31
            IEXT = 447.06

      ELSEIF(MONTH.EQ.'FEBRUARY') THEN

         IF(DAY.GT.28.) GO TO 99

            MN = 2
            LASTDM = 28
            IEXT = 443.89

      ELSEIF(MONTH.EQ.'MARCH') THEN
```

```
      MN = 3
      LASTDM = 31
      IEXT = 437.55

ELSEIF(MONTH.EQ.'APRIL')THEN

   IF(DAY.GT.30) GO TO 99
      MN = 4
      LASTDM = 30
      IEXT = 431.21

ELSEIF(MONTH.EQ.'MAY') THEN

      MN = 5
      LASTDM = 31
      IEXT = 424.87

ELSEIF(MONTH.EQ.'JUNE') THEN

   IF(DAY.GT.30.) GO TO 99

      MN = 6
      LASTDM = 30
      IEXT = 421.70

ELSEIF(MONTH.EQ.'JULY') THEN

      MN = 7
      LASTDM = 31
      IEXT = 421.70

ELSEIF(MONTH.EQ.'AUGUST') THEN

      MN = 8
      LASTDM = 31
      IEXT = 424.87

ELSEIF(MONTH.EQ.'SEPTEMBER') THEN

   IF(DAY.GT.30.) GO TO 99

      MN = 9
      LASTDM = 30
      IEXT = 431.21

ELSEIF(MONTH.EQ.'OCTOBER') THEN

      MN = 10
      LASTDM = 31
      IEXT = 437.55
```

```
      ELSEIF(MONTH.EQ.'NOVEMBER') THEN

         IF(DAY.GT.30.) GO TO 99

            MN = 11
            LASTDM = 30
            IEXT = 443.89

      ELSEIF(MONTH.EQ.'DECEMBER') THEN

            MN = 12
            LASTDM = 31
            IEXT = 447.06

      ELSE

99       WRITE(1,13)
         GO TO 100

      ENDIF

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE DAYS(KDL,DAYS1,FACTOR,MCWB,TEMP)
C-----------------------------------------------------------------------

      REAL*4 MCWB

      IF(MCWB.LT.0.160) THEN

         A = (-0.025)
         B = 4.202

      ELSEIF(MCWB.LT.0.185) THEN

         A = (-0.025)
         B = 3.560

      ELSEIF(MCWB.LT.0.210) THEN

         A = (-0.024)
         B = 3.073

      ELSEIF(MCWB.LT.0.235) THEN

         A = (-0.024)
         B = 2.753
```

```
 ELSEIF(MCWB.LT.0.265) THEN

    A = (-0.023)
    B = 2.417

 ELSEIF(MCWB.LT.0.285) THEN

    A = (-0.023)
    B = 2.204

 ELSEIF(MCWB.LT.0.315) THEN

    A = (-0.024)
    B = 2.113

 ELSE

    WRITE(1,*) 'THE MOISTURE CONTENT IS TOO HIGH TO STORE'
$,'THE GRAIN.'
    DAYS = 0.
    RETURN

 ENDIF

 DAYS = 10.**(A*TEMP+B)
 DAY = FACTOR*DAYS

 IF(INT(DAYS1).NE.0) THEN

    IF(DAYS1.GT.DAY) THEN

       WRITE(16,100)
       WRITE(16,101)DAYS1,DAY
       DAY = DAYS1

    ELSE

       WRITE(16,101)DAYS1,DAY
       DAY = DAYS1

    ENDIF

 ELSE

    WRITE(16,102)DAY

 ENDIF

 KDL = NINT(DAY)
```

```
100   FORMAT(//5X,'The time specified by the user to dry corn is',
     $        /5X,'greater than the theoretical time. However, '
     $        5X,'the model will use time specified by the user.')
101   FORMAT(//5X,'THE TIME SPECIFIED BY THE USER TO DRY CORN ',
     $        'IS ',F5.1,' DAYS.'/5X,'THE TIME ALLOWED TO '
     $       ,'STORE THE CORN AT THE INITIAL M.C.,'/5X,
     $       'BEFORE 0.5% OF THE DRY MATTER OF CORN IS LOST,'
     $       /5X,'IS ',F5.1,' DAYS.')
102   FORMAT(//5X,'THE TIME ALLOWED TO STORE CORN AT THE INITIAL',
     $    ' M.C.,'/5X,'BEFORE 0.5% OF THE DRY MATTER CONTENT OF',
     $     ' CORN IS LOST,'/5X,'IS ',F5.1,' DAYS.')


      RETURN
      END


C-----------------------------------------------------------------------
      FUNCTION DBPS(PS)
C-----------------------------------------------------------------------

      DATA A1/185.245/,A2/.1166787/,A3/5.525642/,A4/-94.2275/,
     1B1/92.29778/,B2/.2226828/,B3/12.88743/,B4/9.415002/,
     1C1/44.11702/,C2/.2949225/,C3/21.77737/,C4/55.98703/

      IF(PS.GE.0.08859) GO TO 1

      DBPS=A1*PS**A2+A3*ALOG(PS)+A4
      RETURN

    1 IF(PS.GE.14.698) GO TO 2

      DBPS=B1*PS**B2+B3*ALOG(PS)+B4
      RETURN

    2 DBPS=C1*PS**C2+C3*ALOG(PS)+C4
      RETURN

      END


C-----------------------------------------------------------------------
      SUBROUTINE DBRH(DB1,RH,DB,DP)
C-----------------------------------------------------------------------

      DB=DB1
      PS=PSDB(DB)
      DP=DBPS(RH*PS)

      RETURN
      END
```

```
C-----------------------------------------------------------------
      REAL*4 FUNCTION DBTOWB(X)
C-----------------------------------------------------------------

C     THIS FUNCTION DETERMINES MOISTURE CONTENT WET BASIS FROM
C     MOISTURE CONTENT DRY BASIS. INPUT SHOULD BE DECIMAL
C     AND OUTPUT IS DECIMAL.

      DBTOWB = X/(1+X)

      RETURN
      END


C-----------------------------------------------------------------
      FUNCTION DELTA(DAYN)
C-----------------------------------------------------------------

C     THE FUNCTION DELTA CALCULATES THE DECLINATION ANGLE OF THE EARTH
C     AT THE DAY NUMBER DAYN. SINCE THE ARGUMENT OF THE ORIGINAL EQUAT-
C     ION IS IN DEGREES, THEN A CONVERSION HAS TO BE MADE FROM RADIANS
C     TO DEGREES.


      ANGLE = 0.98563 * (DAYN - 173.) * 3.14159/180.
      DELTARAD = ASIN(0.39795 * COS(ANGLE))
      DELTA = DELTARAD * 180./3.14159

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE DRYING(TIME,ASTORAGE,CFM,DEPTH,
     $                  TDP,TO,RHUM,TAMB)
C-----------------------------------------------------------------

      REAL*4 ME,MO
      REAL*4 K,L,M,N

     COMMON/MCLAYER/AVGMC

      ROCORN = 47.32
      B = 6.272
      M = 0.722
      N = 0.8

      CP = 0.24
      ROAIR = 0.0734
```

```
      L = 1258.

      RH = RHDBDP(TO,TDP)
      ME = EMC(RH,TO)/100.

      PS = PSDBDP(TO,TDP)
      V = CFM / (ASTORAGE*60.)
      K = B * (PS/14.22)**M * (V/2.82)**N
      TE = WBDBDP(TO,TDP)
      G = CFM*ROAIR*60. / ASTORAGE
      COEF = L*K*ROCORN / (G*CP)

      TETA = K*1.

      D = COEF*(AVGMC - ME) * DEPTH /(TO - TE)
      AVGC = (1./D) * ALOG((EXP(D) + EXP(TETA) - 1.)/EXP(TETA))
      AVGMC = AVGC * (AVGMC - ME) + ME

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE ECANALYSIS (BU,INTEREST,NBATCH,TYPE)
C-----------------------------------------------------------------------

C     THE FUNCTION OF THIS ROUTINE IS TO CALCULATE THECOST OF DRYING
C     ONE BUSHEL OF CORN AND THE EQUIVALENT ANNUAL COST OF THE
C     SOLAR COLLECTOR.


      COMMON/ABSMATERIAL/ABSABS,ABSANU,ABSEMIS,ABSINI,ABSINS,
     $       ABSMAT,ABSYRS
      COMMON/COVMATERIAL/COVANU,COVEMIS,COVFUNCT,COVINIT,COVINS,
     $       COV1MAT,COV2MAT,COVTL,COVTS,COVYRS
      COMMON/INSMATERIAL/INSANU,INSINI,INSINS,INSMAT,INSRIN,
     $       INSTHIK,INSYRS
      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/FANHEAT/FANINI,FANYRS,HEATINI,HEATYRS,TCEHEAT,
     $              TFANECOST,TGRAINECOST,TFANCOLLE
      COMMON/TOTCOV/TINICOV,TINSCOV,TANUCOV
      COMMON/TOTABS/TINIABS,TINSABS,TANUABS
      COMMON/TOTINS/TINIINS,TINSINS,TANUINS
      COMMON/TCOST/ANCOLCOST,TANUALC,CORNBU
      COMMON/TENERGY/TEFAN,TFANGRAINE,TOTLPGAS,LPGSAV


      CHARACTER*18 ABSMAT
      CHARACTER*18 COV1MAT,COV2MAT
      CHARACTER*6 COVFUNCT
      CHARACTER*18 INSMAT
```

```
      REAL*4 INSTHIK,INSINI,INSINS,INSANU,INSYRS,INSRIN
      REAL*4 INTEREST
      REAL*4 LPGSAV

      INTEREST = INTEREST/100.

      IF(TYPE.EQ.3.0) THEN

         TINICOV = 0.
         TINSCOV = 0.
         TANUCOV = 0.

         ANCOV = 0.

      ELSE

         TINICOV = ACOV*COVINIT
         TINSCOV = ACOV*COVINS
         TANUCOV = ACOV*COVANU

         ANCOV = ANUAL(TINICOV+TINSCOV,INTEREST,COVYRS)

      ENDIF

      TINIABS = AABS*ABSINI
      TINSABS = AABS*ABSINS
      TANUABS = AABS*ABSANU

      ANABS = ANUAL(TINIABS + TINSABS,INTEREST,ABSYRS)

      TINIINS = ABOT*INSINI
      TINSINS = ABOT*INSINS
      TANUINS = ABOT*INSANU

       ANINS = ANUAL(TINIINS + TINSINS,INTEREST,INSYRS)

C     CALCULATE EQUIVALENT ANNUAL COST.

      ANCOLCOST = ANCOV + ANABS + ANINS

C     CALCULATE ANUAL FIXED COST.

      TANUALC = ANCOV + ANABS + ANINS
     $        + ANUAL(FANINI,INTEREST,FANYRS)
     $        + ANUAL(HEATINI,INTEREST,HEATYRS)
     $        + TFANECOST + TGRAINECOST + TCEHEAT


C     CALCULATE COST TO DRY ONE BUSHEL OF CORN.
```

```
      CORNBU = TANUALC/(BU * NBATCH)

      INTEREST = INTEREST*100.

      RETURN
      END


C-----------------------------------------------------------------
      REAL*4 FUNCTION EMC(RH,TO)
C-----------------------------------------------------------------

C     CALCULATES THE EQUILIBRIUM M.C. %d.b. OF CORN FOR GIVEN CONDITIONS
C     OF THE AIR.

C     THIS EQ. IS EMPIRICAL. IT WAS PROPOSED BY THOMPSON,1967.

      F1  ALOG(1. - RH)
      F2 = (-3.195E-05) * (TO + 50)
      EMC = SQRT(F1/F2)

      RETURN
     END


C-----------------------------------------------------------------
      FUNCTION EOT(DAYN)
C-----------------------------------------------------------------

C      THE FUNCTION EQUATION OF TIME (EOT) CALCULATES THE CORRECTION TO
BE
C     MADE TO THE SOLAR TIME. THIS IS AN APPROXIMATE EQUATION. SINCE THE
C     ARGUMENTS ARE IN DEGREES, THEY HAVE TO BE CHANGED FOR CALCULATING
C     THOSE IN THE COMPUTER.


      X = 360. * (DAYN-1.)/365.242 * 3.14159/180.
      EOT =  (0.1236*SIN(X) - 0.0043*COS(X) + 0.1538*SIN(2*X) +
     $        0.0608*COS(2*X))

      RETURN
      END


C-----------------------------------------------------------------
      REAL*4 FUNCTION FANCOLLE(CFM)
C-----------------------------------------------------------------
```

```
C     ESTIMATES THE ENERGY REQUIRED FOR THE FAN TO MOVE THE AIR
C     THROUGH THE COLLECTOR. THIS ENERGY IS GIVEN IN KW-HR.

C     ASSUMES PRESSURE DROP THROUGH THE COLLECTOR OF 0.25 IN.WATER.

      EFF = 0.60

      DELTAP = 0.25
      FANCOLLE = 0.00012 * DELTAP * CFM / EFF

      RETURN
      END


C-----------------------------------------------------------------
      REAL*4 FUNCTION FANGRAINE(ASTORAGE,CFM,DEPTH)
C-----------------------------------------------------------------

C     CALCULATES THE ENERGY REQUIRED FOR THE FAN TO MOVE THE
C     AIR THROUGH THE GRAIN. PRESSURE DROP THROUGH THE GRAIN
C     IS BASED ON AN EMPIRICAL EQUATION BY HUKILL AND SHEDD,
C     1955.

C     ASSUMES EFFICIENCY OF ELECTRIC FAN OF 60%.

      EFF = 0.60

      VEL = CFM/ASTORAGE
      DPPRIME = 0.00065*VEL**2 / ALOG(1. + 0.156*VEL)
      DELTAP = DPPRIME * DEPTH
      FANGRAINE = 0.00012*CFM*DELTAP/EFF

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE GAUSSJ(N,SIGMA,R)
C-----------------------------------------------------------------

      REAL*4 R(3),SIGMA(3)
      COMMON/PARTDER/C(3,3)

      DO 100 K = 1,N

         TEMP = 1./C(K,K)

         DO 101 J = K,N
            C(K,J) = C(K,J) * TEMP
101      CONTINUE
```

```
         R(K) = R(K) * TEMP

         DO 102 J = 1,N

            IF(K.EQ.J) GO TO 102

               TEMP = C(J,K)

               DO 103 L = K,N
                  C(J,L) = C(J,L) - C(K,L)*TEMP
103            CONTINUE

            R(J) = R(J) - R(K)*TEMP

102      CONTINUE

100   CONTINUE

      DO 104 I=1,N
         SIGMA(I) = R(I)
104   CONTINUE

      RETURN
      END


C-----------------------------------------------------------------
      REAL*4 FUNCTION HLDB(DB)
C-----------------------------------------------------------------

      DBB=DB+459.69

      IF(DBB-491.69) 1,2,2
    1 HLDB=1220.884-0.05077*(DBB-459.69)
      RETURN

    2 IF(DBB-609.69) 3,4,4
    3 HLDB=1075.8965-0.56983*(DBB-459.69)
      RETURN

    4 DUMM=(1354673.214-0.91252756*DBB*DBB)
      HLDB=SQRT(DUMM)

      RETURN
      END


C-----------------------------------------------------------------
      REAL*4 FUNCTION HSR(LAT,DEC)
C-----------------------------------------------------------------
```

```
      REAL LAT

      HSR = ACOS(-(TAN(LAT)*TAN(DEC)))

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE INPUTS1(DELTAT,ELCT,LPGAS)
C-----------------------------------------------------------------------

C     THIS FUNCTION ENTERS THE TEMPERATURE INCREMENT FOR THE
C     AIR AT NIGHT.THE TEMPERATURE INCREMENT DETERMINES HOW
C     MUCH LPGAS WOULD BE USED TO HEAT THE AIR.

     REAL*4 LPGAS

1     WRITE(1,10)
      READ(1,11,ERR=100)DELTAT
      TEMPINC = DELTAT

      IF(DELTAT.LT.0.0.OR.DELTAT.GT.70)THEN

100      WRITE(1,12)
         GO TO 1

      ENDIF

2     LPGAS = 1.00
      ELCT = 0.05
      WRITE(1,13)
      WRITE(1,14) LPGAS,ELCT
      WRITE(1,15)
      READ(1,16) ANS

      IF(ANS.EQ.'N') RETURN

      WRITE(1,17)
      READ(1,11,ERR=150)LPGAS
      WRITE(1,18)
      READ(1,11,ERR=150) ELCT

      IF(LPGAS.GT.2.0) THEN

150      WRITE(1,12)
         GO TO 2

      ENDIF

      IF(ELCT.GT.0.10) THEN
```

```
         WRITE(1,12)
         GO TO 2

       ENDIF

10     FORMAT(15(/),5X,'HOW MANY DEGREES F WOULD YOU LIKE TO HEAT'
     $        ' THE AIR AT NIGHT?'/5X,'(0.0<DELTAT>70.0)')
11     FORMAT(F7.0)
12     FORMAT(5(/),5X,'CHECK YOUR DATA AND INPUT IT AGAIN.')
13     FORMAT(15(/),10X,'VALUES FOR LPGAS AND ELECTRICITY'
     $       ' ARE')
14     FORMAT(//,10X,'LPGAS ',F5.2,' $/GL.'//,10X,
     $       'ELECTRICITY ',F5.2,' $/KW-HR'//)
15     FORMAT(5(/),10X,'DO YOU WANT TO CHANGE THESE VALUES ?'
     $       /,10X,'(Y/N)')
16     FORMAT(A1)
17     FORMAT(5(/),10X,'ENTER NEW VALUE FOR LPGAS. ($/GL.)')
18     FORMAT(5(/),10X,'ENTER NEW VALUE FOR ELECTRICITY. ($/KW-HR)')


       RETURN
       END


C-----------------------------------------------------------------------
       REAL*4 FUNCTION KB(KT)
C-----------------------------------------------------------------------

       REAL*4 KT

       IF (KT.GT.0.0.AND.KT.LT.0.05) THEN

          A = 0.04
          B = 0.0

       ELSEIF (KT.LT.0.15) THEN

          A = 0.01
          B = 0.002

       ELSEIF (KT.LT.0.25) THEN

          A = 0.06
          B = (-0.006)

       ELSEIF (KT.LT.0.35) THEN

          A = 0.32
          B = (-0.071)
```

```
      ELSEIF (KT.LT.0.45) THEN

        A = 0.82
        B = (-0.246)

      ELSEIF (KT.LT.0.55) THEN

        A = 1.56
        B = (-0.579)

      ELSEIF (KT.LT.0.65) THEN

        A = 1.69
        B = (-0.651)

      ELSEIF (KT.LT.0.75) THEN

        A = 1.49
        B = (-0.521)

      ELSEIF (KT.LT.0.85) THEN

        A = 0.27
        B = 0.395

      ELSEIF (KT.LT.0.0) THEN

        WRITE(1,*)' CHECK THE WEATHER DATA FILE.'

      ELSE

        A = 1.
        B = 0.0

      ENDIF

      KB = A*KT + B

      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE PERFORMANCE (TAMB,WIND,TYPE,SHAPE)
C-----------------------------------------------------------------------

C     VARIABLES:  NO: NUMBER OF SEGMENTS IN COLLECTOR.
C                 L1,L2,L3: LENGTH,WIDTH,HEIGTH (FT.) OF COLLECTOR.
C                 ABS: OPTICAL PROPERTIES OF ABSORBER.
C                 BOT: THERMAL PROPERTIES OF BOTTOM.
C                COV: OPTICAL PROPERTIES OF COVER.
C                 TAMB: AMBIENT TEMPERATURE DEG.F.
```

```
C                RAD: HORIZONTAL RADIATION BTU/HR-SQRT. FT.
C                INCID: ANGLE OF INCIDENCE BETWEEN COLLECTOR SURFACE
C                      AND BEAM RADIATION, RAD.
C                TYPE: COLLECTOR TYPE.
C                SHAPE: COLLECTOR SHAPE.
C                CFM: AIRFLOW RATE, CFM.
C                TFOUT: OUTLET TEMPERATURE OF THE AIR, DEG. F.
C                EFF: THERMAL EFFICIENCY OF COLLECTOR, %.
C                QUSEFUL: USEFUL HEAT, BTU.
C               AIRVEL: AIR VELOCITY THROUGHOUT COLLECTOR,FT./MIN.
C                G :AIR MASS RATE PER UNIT AREA OF ABSORBER, CFM/SQR.FT
ABS.


      COMMON/COVMATERIAL/COVANU,COVEMIS,COVFUNCT,COVINIT,COVINS,
     $       COV1MAT,COV2MAT,COVTL,COVTS,COVYRS
      COMMON/AIRVARIABLES/AIRMASS,AIRVEL,CFM
      COMMON/INSOLATION/IBT,IDT,INCID,DEGINCID
      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/AIRPROPERTIES/CP,K,MU,ROAIR
      COMMON/MATCOLT/A1S,A2S,A3S,E1L,E2L,E12L,E23L,
     $       RBOTTOM,RO1S,RO12S,TAULONG,TAUSHORT
      COMMON/COLTOUT/EFF,QUSEFUL,TOUT
      COMMON/DIMENSIONS/NO,L1,L2,L3
      COMMON/PERFVAR/HW,QO,TAU1QO,TSKY
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2
      COMMON/TEMPERATURES/T1,T2,T3,TF,TF1,TF2
      COMMON/PARTDER/DF11,DF12,DF13,DF21,DF22,DF23,DF31,DF32,DF33


      REAL*4 HS,HSR,IB,IBT,ID,IDT,IEXT,IMC,INCID
      REAL*4 CP,K,MU,PI,ROAIR
      REAL*4 L1,L2,L3
      REAL*4 H1,H2,H2P,H2PP,H3

      EXTERNAL TRANS

      CHARACTER*72 WORD(30),ATYPE(15),ASHAPE(17)
      CHARACTER*19 INSHAPE,INTYPE
      CHARACTER*18 ABSMAT
      CHARACTER*18 COV1MAT,COV2MAT
      CHARACTER*6 COVFUNCT
      CHARACTER*18 INSMAT
      CHARACTER*80 HTABLE(15)
      CHARACTER*10 MONTH(12)
      CHARACTER*8 FNAME
```

```
      REAL*4 COVANU,COVEMIS,COVINIT,COVINS,COVTL,COVTS,COVYRS
      REAL*4 SIGMA(3),F(3),DF(3,3),R(3)
      REAL*4 IBT,IDT,INCID
      REAL*4 HW


C     ......CONSTANTS USED ON THE ROUTINE:

C                   TOLNRAP: MAXIMUM TOLERANCE IN NEWTON-RAP. ALGORITHM.
C                   ITERMAX: MAXIMUM NUMBER OF ITERATIONS.
C                   Y: LENGTH OF EACH SEGMENT OF COLLECTOR.
C                   CP: SPECIFIC HEAT OF AIR, BTU/LB-DEG. F.


      TOLNRAP = 1.5E-02
      ITERMAX = 50
      Y = L1/NO

C      .....CONVERSION FROM DEG. F TO DEG. RANKINE.....
C      .....INITIATE INLET AIR TEMPERATURE.....


      TAMB = TAMB + 459.69
      T1 = T1 + 459.69
      T2 = T2 + 459.69

      IF(TYPE.EQ.2.0) THEN

         TIN1 = TAMB
         TIN2 = TAMB

         T3 = T3 + 459.69

      ELSE

         TIN = TAMB

      ENDIF

C     .....INITIATE ITERATIONS COUNTER.....

      ITER = 1

C     .....DEFINE FLAG NEWTON.....

      NEWTON = 1

C     .....CALCULATION OF VARIABLES INDEPENDENT OF COLL. TEMP......

      HW = 1.00 + 0.3*WIND
      TSKY = 0.0994 * (TAMB/1.8)**1.5
```

```
C        .....DO  LOOP  TO  CALCULATE  TEMPERATURES  AT  EACH  SEGMENT  OF
COLLECTOR.....

      DO 1000 ISEG=1,NO

C     .....CALCULATION OF FUNCTIONS AND THEIR DERIVATIVES OF HEAT EQS.
C          FOR SEGMENT OF COLLECTOR.....

999   IF(TYPE.EQ.1.0) THEN

         NEQ = 2
         CALL CONVECT1(ISEG)
         CALL COLT1(TAMB,F,DF)

      ELSEIF(TYPE.EQ.2.0) THEN

         NEQ = 3
         CALL CONVECT2(ISEG)
         CALL COLT2(TAMB,F,DF)

      ELSE

         NEQ = 2
         CALL CONVECT3(ISEG)
         CALL COLT3(TAMB,F)

      ENDIF

C     .....CHANGE SIGN OF THE FUNCTION 'F'.....

      DO 15 I = 1,NEQ
         R(I) = (-1)*F(I)
15    CONTINUE

C     .....FIND TEMPERATURE INCREMENTS USING GAUSS-SIEDEL.....

      CALL GAUSSJ(NEQ,SIGMA,R)

      T1 = T1 + SIGMA(1)
      T2 = T2 + SIGMA(2)

      IF (TYPE.EQ.2.0) THEN

         T3 = T3 + SIGMA(3)

      ENDIF

C     .....DO LOOP TO COMPARE INCREMENTS WITH MAX. TOLERANCE.....

      DO 1500 I=1,NEQ
```

```
         IF (ABS(SIGMA(I)).GT.TOLNRAP) NEWTON =0

1500  CONTINUE

C        .....ALGORITHM TO DECIDE IF INCREMENTS ARE SMALL ENOUGH OR
NOT.....

      IF (NEWTON.EQ.0) THEN

         IF (ITER+1.GT.ITERMAX) THEN
            WRITE(1,*) 'THE SYSTEM DOES NOT CONVERGE.'
            STOP
         ENDIF

         ITER = ITER + 1
         NEWTON =1
         GO TO 999

      ENDIF

C     .....CALCULATE AVG. AIR TEMP. AT SEGMENT, OUTLET AIR TEMP.
C     AND UPDATE INLET TEMP. OF THE NEXT SEGMENT.....

      CALL TEMPF(TYPE)

      IF(TYPE.EQ.2.0) THEN

         TOUT1 = 2.0 * TF1 - TIN1
         TOUT2 = 2.0 * TF2 - TIN2
         TOUT = (G1 * TOUT1 + G2 * TOUT2) / GCROSS

         TIN1 = TOUT1
        TIN2 = TOUT2

      ELSE

         TOUT = 2.0 * TF - TIN
         TIN = TOUT

      ENDIF

      ITER = 1

1000  CONTINUE

C     .....END LOOP TO CALCULATE THE OUTLET AIR TEMP......


C     .....CALCULATION OF OUTPUT VARIABLES.....
```

```
      QUSEFUL = GCROSS * CP * (TOUT-TAMB)
      EFF = QUSEFUL/(QO*AABS)

C      .....CONVERSION FROM DEG. RANKINE TO DEG. F.....

      TAMB = TAMB - 459.69
      T1 = T1 - 459.69
      T2 = T2 - 459.69

      IF(TYPE.EQ.2.0) THEN

         TIN1 = TIN1 - 459.69
         TIN2 = TIN2 - 459.69
         T3 = T3 - 459.69

      ENDIF

101   FORMAT(///3X,'SEGMENT',3X,'ITERATION',5X,'F(1)',9X,'F(2)',
     $       9X,'DF(1)',8X,'DF(2)'//)
102   FORMAT(4X,I3,9X,I3,6X,E10.3,5(3X,E10.3))
106   FORMAT(3(3X,F7.3))

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE PRINTABLES(FNAME,NH,N,NB,NPAGE)
C-----------------------------------------------------------------------

C     VARIABLES:  FNAME: NAME OF THE FILE TO BE PRINTED.
C                 NH: NUMBER OF LINES USED FOR HEADINGS.
C                 N:      NUMBER OF REFERENCES. IT SHOULD BE CHANGED
C                         WHEN ADDING OR DELETING REFERENCE MATERIALS.
C                         THIS NUMBER HAS TO BE CHANGED ON THE MAIN
C                         PROGRAM.
C                 NB:     NUMBER OF LINES AT THE BOTTOM OF TABLE.
C                 NPAGE: NUMBER OF REFERENCES PRINTED AT A TIME.

      COMMON/ABSMATERIAL/ABSABS,ABSANU,ABSEMIS,ABSINI,ABSINS,
     $       ABSMAT,ABSYRS
     COMMON/COVMATERIAL/COVANU,COVEMIS,COVFUNCT,COVINIT,COVINS,
     $       COV1MAT,COV2MAT,COVTL,COVTS,COVYRS
      COMMON/INSMATERIAL/INSANU,INSINI,INSINS,INSMAT,INSRIN,
     $       INSTHIK,INSYRS

      CHARACTER*18 ABSMAT
      CHARACTER*18 COV1MAT,COV2MAT
      CHARACTER*6 COVFUNCT
      CHARACTER*18 INSMAT
      CHARACTER*8 FNAME
```

```
      CHARACTER*80 HTABLE(15),TABLE(60),BTABLE(10)

      OPEN(103,FILE = FNAME)

1000  FORMAT(A80)

      IF(FNAME.EQ.'COVER') THEN

         NTABLE = 2*N

      ELSE

         NTABLE = N

      ENDIF

      READ(103,1000)(HTABLE(I),I=1,NH)
      READ(103,1000)(TABLE(I),I=1,NTABLE)
      READ(103,1000)(BTABLE(I),I=1,NB)
      CLOSE(103)

      NCHECK = 0

100   WRITE(1,1000)(HTABLE(I),I=1,NH)

      IF(NCHECK + NPAGE.GT.NTABLE)THEN

         N1 = NTABLE

      ELSE

         N1 = NCHECK + NPAGE

      ENDIF

      WRITE(1,1000)  (TABLE(I),I=NCHECK+1,N1)
      WRITE(1,1000) (BTABLE(I),I= 1,NB)
      READ(1,12,ERR=300) NUMBER
12    FORMAT(I2)

      IF(NUMBER.EQ.0) THEN

         NCHECK = 0
         GO TO 100

      ELSEIF(NUMBER.GT.N) THEN

         WRITE(1,*)' CHECK YOUR REFERENCE NUMBER AND INPUT IT AGAIN.'
         NCHECK= 0
         GO TO 100
```

```
      ELSE

         CALL READTABLES(FNAME,NH,N,NUMBER)
         RETURN

      ENDIF

300   IF(N1.EQ.NTABLE) THEN

200      WRITE(1,*)' THIS IS THE END OF THE TABLE.'
         WRITE(1,*)' DO YOU WANT TO SEE THE WHOLE TABLE AGAIN ? (Y/N)'
         READ(1,13) ANS
13       FORMAT(A1)

         IF(ANS.EQ.'Y') THEN

            NCHECK = 0
            GO TO 100

         ENDIF

         WRITE(1,*)' INPUT THE REFERENCE NUMBER OF THE MATERIAL'
         WRITE(1,*)' YOU WANT TO USE.'
         READ(1,12,ERR = 200) NUMBER

      ELSE

         NCHECK = NCHECK + NPAGE
         GO TO 100

      ENDIF

      IF(NUMBER.GT.N) THEN

         WRITE(1,*)' CHECK YOUR REFERENCE NUMBER AND INPUT IT AGAIN.'
         NCHECK = 0
         GO TO 100

      ENDIF

      CALL READTABLES(FNAME,NH,N,NUMBER)

      RETURN
      END


C-----------------------------------------------------------------------
      FUNCTION PSDB(DB)
C-----------------------------------------------------------------------

      EXTERNAL PSDB1
```

```
      DOUBLE PRECISION R,A,B,C,D,E,F,G

      DATA R/.320618D+04/,A/-.274055D+05/,B/.541896D+02/,C/-.45137D-01/,
     1D/.215321D-04/,E/-.462027D-08/,F/.241613D+01/,G/.121547D-02/

      DBB=DB+459.69

      IF(DBB-491.69) 1,1,2

    1    PS=EXP(23.39-11286.65/(DBB)-.46*ALOG(DBB))
         P1=2.0*PS
         P2=0.3*PS
         DB1=DB
         CALL SEARC1(PSDB1,P1,P2,0.01,PS,DB1,DB1)
         PSDB=PS
         RETURN

      2        PSDB=R*DEXP((A+B*DBB+C*DBB**2+D*DBB**3+E*DBB**4)/(F*DBB-
G*DBB**2))
         RETURN

      END


C-----------------------------------------------------------------
      FUNCTION PSDB1(PS,DB,DB)
C-----------------------------------------------------------------

      PSDB1=DB-DBPS(PS)

      RETURN
      END


C-----------------------------------------------------------------
      FUNCTION PSDBDP(DB,DP)
C-----------------------------------------------------------------

      PSDBDP=PSDB(DB)

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE READTABLES(FNAME,NH,N,NUMBER)
C-----------------------------------------------------------------

      COMMON/ABSMATERIAL/ABSABS,ABSANU,ABSEMIS,ABSINI,ABSINS,
     $       ABSMAT,ABSYRS
```

```
      COMMON/COVMATERIAL/COVANU,COVEMIS,COVFUNCT,COVINIT,COVINS,
     $       COV1MAT,COV2MAT,COVTL,COVTS,COVYRS
      COMMON/INSMATERIAL/INSANU,INSINI,INSINS,INSMAT,INSRIN,
     $       INSTHIK,INSYRS

      CHARACTER*18 ABSMAT
      CHARACTER*19 INSHAPE,INTYPE
      CHARACTER*18 COV1MAT,COV2MAT,INSMAT,ABSMAT
      CHARACTER*18 INSMAT
      CHARACTER*6 COVFUNCT
      CHARACTER*8 FNAME
      CHARACTER*80 HTABLE(15)

      REAL INSTHIK,INSINI,INSINS,INSANU,INSYRS,INSRIN

      OPEN(103,FILE = FNAME)

      READ(103,1000) (HTABLE(I),I=1,NH)

      IF(FNAME.EQ.'COVER') THEN

         DO 100 I=1,NUMBER
           READ(103,1001) COV1MAT,COVINIT,COVINS,COVANU,COVYRS,COVTL
     $         ,COVTS,COVFUNCT,COVEMIS,COV2MAT
100      CONTINUE

      ELSEIF(FNAME.EQ.'ABSORB') THEN

         DO 200 I=1,NUMBER
            READ(103,1002)ABSMAT,ABSINI,ABSANU,ABSINS,ABSYRS
     $           ,ABSABS,ABSEMIS
200      CONTINUE

      ELSE

         DO 300 I=1,NUMBER
            READ(103,1003)INSMAT,INSTHIK,INSINI,INSINS,INSANU
     $           ,INSYRS,INSRIN
300      CONTINUE

      ENDIF

      CLOSE (103)

1000  FORMAT(A80)
1001  FORMAT(6X,A18,F5.2,1X,F5.2,3X,F5.2,5X,F2.0,5X,F4.1,
     $     3X,F4.1,2X,A6,1X,F4.1/6X,A18)
1002  FORMAT(7X,A18,F5.2,1X,F5.2,2X,F5.2,4X,F2.0,10X,F4.1,8X,F4.1)
1003  FORMAT(8X,A18,2X,F5.2,F5.2,3X,F5.2,F5.2,5X,F2.0,5X,F5.2)
```

```
      RETURN
      END

C-----------------------------------------------------------------
      SUBROUTINE READWEATHER(DAY,MN,LASTDM)
C-----------------------------------------------------------------

C      THIS SUBROUTINE READS THE WEATHER DATA FROM THE FILE(S) NAMED
C      WITH THE MONTH IT CORRESPONDS.
C      THE TIME REQUIRED TO DRY ONE BATCH IS ASSUMED TO BE LESS
C      THAN 15 DAYS.

C           INPUT VARIABLES:

C           DAY: DAY OF THE MONTH, REAL.
C           MN: MONTH NUMBER, REAL.
C           LASTDM: LAST DAY OF THE MONTH, REAL.
C           JULIAN : JULIAN DAY, INTEGER.
C           TIME : TIME, REAL.
C           WIND: WIND SPEED, MPH, REAL.
C           TEMP: AMBIENT TEMPERATURE DEG. F, REAL.
C           QRAD: SOLAR RADIATION BTU/(SQRT. FT-HR), REAL.
C           RHUM : RELATIVE HUMIDITY %, REAL.

      COMMON/WEATHER/JULIAN(31),TIME(31,24),WIND(31,24),
     $               QRAD(31,24),RHUM(31,24),TEMP(31,24)
      CHARACTER*10 MONTH(12)
      DATA (MONTH(I),I=1,12)/'JANUARY','FEBRUARY','MARCH','APRIL'
     $,'MAY','JUNE','JULY','AUGUST','SEPTEMBER','OCTOBER',
     $'NOVEMBER','DECEMBER'/

      IDAY = INT(DAY)

      OPEN(100,FILE = MONTH(MN))

      KOUNT = 0

      DO 10 K=1,LASTDM

         READ(100,1000)JULIAN(K),ITIME,QRAD(K,1),
     $                 WIND(K,1),TEMP(K,1),RHUM(K,1)
         TIME(K,1) = FLOAT(ITIME)

        DO 11 J = 2,24

            READ(100,1001) ITIME,QRAD(K,J),WIND(K,J),
     $                     TEMP(K,J),RHUM(K,J)
            TIME(K,J) = FLOAT(ITIME)
```

```
11       CONTINUE

10    CONTINUE

      CLOSE(100)

      DO 12 K = IDAY,LASTDM

         KOUNT = KOUNT + 1
         JULIAN(KOUNT) = JULIAN(K)

         DO 13 J = 2,24

            TIME(KOUNT,J) = TIME(K,J)
            QRAD(KOUNT,J) = QRAD(K,J)
            WIND(KOUNT,J) = WIND(K,J)
            TEMP(KOUNT,J) = TEMP(K,J)
            RHUM(KOUNT,J) = RHUM(K,J)

13       CONTINUE

12    CONTINUE

      IF(IDAY + 15.GT.LASTDM) THEN

         IF(MN.EQ.12) THEN

            OPEN(100,FILE = MONTH(1))

         ELSE

            OPEN(100,FILE = MONTH(MN + 1))

         ENDIF

         DO 20 K = 1,14

            KOUNT = KOUNT + 1
            READ(100,1000)JULIAN(KOUNT),ITIME,QRAD(KOUNT,1),
     $                    WIND(KOUNT,1),TEMP(KOUNT,1),RHUM(KOUNT,1)
            TIME(KOUNT,1) = FLOAT(ITIME)

            DO 21 J = 2,24

               READ(100,1001)ITIME,QRAD(KOUNT,J),WIND(KOUNT,J),
     $                       TEMP(KOUNT,J),RHUM(KOUNT,J)
               TIME(KOUNT,J) = FLOAT(ITIME)

21          CONTINUE

20       CONTINUE
```

```
         CLOSE(100)

      ENDIF

1000  FORMAT(1X,I3,2X,I3,2X,F5.1,2X,F5.1,2X,F6.2,2X,F4.0)
1001  FORMAT(6X,I3,2X,F5.1,2X,F5.1,2X,F6.2,2X,F4.0)

      RETURN
      END


C-----------------------------------------------------------------------
      FUNCTION RHDBDP(DB,DP)
C-----------------------------------------------------------------------

      RHDBDP=PSDB(DP)/PSDB(DB)

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE SEARC1(FUNCT,S1,S2,ESP,ANSWR,P1,P2)
C-----------------------------------------------------------------------

      EXTERNAL FUNCT

      T1=FUNCT(S1,P1,P2)
      T2=FUNCT(S2,P1,P2)
      T12=T1*T2

      IF(T12.GT.0.0) GO TO 300

  100 WI=(S1+S2)/2.0
      TI=FUNCT(WI,P1,P2)

      IF(ABS(TI).LE.ESP) GO TO 200

      IF(TI.GT.0.0.AND.T1.GT.0.0) S1=WI
      IF(TI.LT.0.0.AND.T1.LT.0.0) S1=WI
      IF(TI.LT.0.0.AND.T2.LT.0.0) S2=WI
      IF(TI.GT.0.0.AND.T2.GT.0.0) S2=WI
      GO TO 100

  200 ANSWR=WI

      RETURN

  300 DS=ABS(S1-S2)
```

```
      IF(DS.GT.ESP) GO TO 400

      ANSWR=(S1+S2)/2.0

      RETURN

  400 WRITE(1,301) S1,S2,ESP
  301 FORMAT(1H0,'*** NO CONVERGENCE ***,   S1=',F12.5,'  S2=',F12.5,
     *'    ESP=',F10.5)

      ANSWR=99999.

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE SEARCH(FUNCT,S1,S2,ESP,ANSWR,P1,P2)
C-----------------------------------------------------------------------

      EXTERNAL FUNCT
C
      T1=FUNCT(S1,P1,P2)
      T2=FUNCT(S2,P1,P2)
      T12=T1*T2

      IF(T12.GT.0.0) GO TO 300

  100 WI=(S1+S2)/2.0
      TI=FUNCT(WI,P1,P2)

      IF(ABS(TI).LE.ESP) GO TO 200

      IF(TI.GT.0.0.AND.T1.GT.0.0) S1=WI
      IF(TI.LT.0.0.AND.T1.LT.0.0) S1=WI
      IF(TI.LT.0.0.AND.T2.LT.0.0) S2=WI
      IF(TI.GT.0.0.AND.T2.GT.0.0) S2=WI
      GO TO 100

  200 ANSWR=WI
      RETURN

  300 DS=ABS(S1-S2)

      IF(DS.GT.ESP) GO TO 400

      ANSWR=(S1+S2)/2.0
      RETURN

  400 WRITE(1,301) P1,P2
   30 FORMAT(1H0,'*** NO CONVERGENCE ***,   P1=',F12.5,'  P2=',F12.5)
```

```
      ANSWR=9999.

      RETURN
      END


C-----------------------------------------------------------------
      FUNCTION STIME(LST,LOLONG,DAY)
C-----------------------------------------------------------------

      REAL LST,LOLONG

      EQTIM = EOT(DAY)
      STIME = LST + EOT(DAY) - AMOD(LOLONG,15.)/15.

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE SUBOUT1 (ASTORAGE,AW,BU,CITYNAME,DEPTH,DAY,
     $       FMCWB,G,IMCWB,LAT,LOLONG,MONTH,SHAPE,SIGMA,TYPE
     $       ,TOTBU)
C-----------------------------------------------------------------

      COMMON/ABSMATERIAL/ABSABS,ABSANU,ABSEMIS,ABSINI,ABSINS,
     $       ABSMAT,ABSYRS
      COMMON/COVMATERIAL/COVANU,COVEMIS,COVFUNCT,COVINIT,COVINS,
     $       COV1MAT,COV2MAT,COVTL,COVTS,COVYRS
      COMMON/INSMATERIAL/INSANU,INSINI,INSINS,INSMAT,INSRIN,
     $       INSTHIK,INSYRS
      COMMON/MATCOLT/A1S,A2S,A3S,E1L,E2L,E12L,E23L,
     $       RBOTTOM,RO1S,RO12S,TAULONG,TAUSHORT
      COMMON/AIRVARIABLES/AIRMASS,AIRVEL,CFM
      COMMON/DIMENSIONS/NO,L1,L2,L3
      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2

      CHARACTER*18 ABSMAT
      CHARACTER*18 COV1MAT,COV2MAT
      CHARACTER*6 COVFUNCT
      CHARACTER*18 INSMAT

      REAL*4 INSTHIK,INSINI,INSINS,INSANU,INSYRS,INSRIN
      REAL*4 L1,L2,L3
      REAL*4 LAT,LOLONG
      REAL*4 IMC,IMCWB,FMC,FMCWB
```

```
 CHARACTER*20 CITYNAME
 CHARACTER*10 MONTH

 WRITE(16,100)
 WRITE(16,101) CITYNAME
 WRITE(16,102) LAT
 WRITE(16,103) LOLONG

 WRITE(16,137) TOTBU
WRITE(16,104) BU

 IMC = IMCWB * 100.
FMC = FMCWB * 100.

 DBIMC = WBTODB(IMCWB) * 100.
 DBFMC = WBTODB(FMCWB) * 100.

 IDAY = INT(DAY)
 ISTORAGE = NINT(ASTORAGE)

 WRITE(16,105) IMC,DBIMC
 WRITE(16,106) FMC,DBFMC
 WRITE(16,107) MONTH,IDAY
WRITE(16,108) ISTORAGE
 WRITE(16,109) DEPTH
 WRITE(16,110)

 IF(TYPE.EQ.1.) THEN
    ASSIGN 111 TO IFMT1
 ELSEIF(TYPE.EQ.2.) THEN
    ASSIGN 112 TO IFMT1
 ELSE
    ASSIGN 113 TO IFMT1
 ENDIF

 WRITE(16,IFMT1)

 IF(SHAPE.EQ.1) THEN
    ASSIGN 114 TO IFMT2
 ELSEIF(SHAPE.EQ.2) THEN
    ASSIGN 115 TO IFMT2
 ELSEIF(SHAPE.EQ.3) THEN
    ASSIGN 116 TO IFMT2
 ELSE
    ASSIGN 117 TO IFMT2
 ENDIF

 WRITE(16,IFMT2)
 WRITE(16,118) L1,L2,L3
```

```
      WRITE(16,119) SIGMA
      WRITE(16,120) AW
      WRITE(16,121)
      WRITE(16,122) COV1MAT
      WRITE(16,123) COVINIT,COVINS,COVANU,COVYRS
      WRITE(16,124)
      WRITE(16,125) COVTL
      WRITE(16,127)
      WRITE(16,125) COVTS
      WRITE(16,129) ABSMAT
      WRITE(16,123) ABSINI,ABSINS,ABSANU,ABSYRS
      WRITE(16,124)
      WRITE(16,126) ABSEMIS
      WRITE(16,127)
      WRITE(16,128) ABSABS
      WRITE(16,130) INSMAT
      WRITE(16,136) INSTHIK
      WRITE(16,123) INSINI,INSINS,INSANU,INSYRS
      WRITE(16,131) RBOTTOM
      WRITE(16,132) ACOV,AABS,ABOT
      WRITE(16,133) CFM,G



100   FORMAT(5(/),5X,'SOLAR DRYING SYSTEM FOR CORN',///)
101   FORMAT(8X,'Location : ',A20)
102   FORMAT(8X,'Latitude : ',T20,F5.2,' deg.')
103   FORMAT(8X,'Longitude : ',T20,F5.2,' deg.')
137   FORMAT(///8X,'Total amount of corn dried annually ',F9.2,
     $       ' bushels.')
104   FORMAT(8X,'Amount of corn dried per batch ',
     $       T40,F8.2,T50,'bushels.')
105   FORMAT(8X,'Initial moisture content is ',F5.2,' %wet'
     $       ' basis, (',F5.2,' % dry basis.)')
106   FORMAT(8X,'Final moisture content is ',F5.2,' %wet'
     $       'basis, (',F5.2,' % dry basis.)')
107   FORMAT(//8X,'Day to start drying :',T31,'Month : ',A10/
     $       T31,'Day : ',I2)
108   FORMAT(8X,'The area of the drying facility is ',I5,' SQR.ft.')
109   FORMAT(8X,'The depth of the grain is ',F5.2,' ft.')
110   FORMAT(//8X,'CHARACTERISTICS OF THE COLLECTOR'///)
111   FORMAT(/8X,'COLLECTOR TYPE I, air flows above the absorber.')
112   FORMAT(/8X,'COLLECTOR TYPE II, air flows on both sides of'
     $       ' the absorber.')
113   FORMAT(/8X,'COLLECTOR TYPE III, air flows underneath the'
     $       ' absorber.')
114   FORMAT(8X,'COLLECTOR CROSS SECTIONAL SHAPE : triangular with a'
     $       ' right angle.')
```

```
115   FORMAT(8X,'COLLECTOR CROSS SECTIONAL SHAPE : triangular with'
     $       ' two angles of equal magnitude.')
116   FORMAT(8X,'COLLECTOR CROSS SECTIONAL SHAPE : rectangular.')
117   FORMAT(8X,'COLLECTOR CROSS SECTIONAL SHAPE : semicircular.')
118   FORMAT(//,8X,'DIMENSIONS :',T24,'Length :',T35,F6.2,' ft.'/T24,
     $       'Width :',T35,F6.2,' ft.'/T24,'Height :',T35,F6.2,'ft.')
119   FORMAT(//8X,'The inclination of the collector surface is ',F5.2,
     $       T61,'deg.')
120   FORMAT(8X,'The orientation from the south to the east is ',F5.2,
     $       T61,'deg.')
121   FORMAT(///8X,'COLLECTOR MATERIALS')
122   FORMAT(//11X,'Cover : ',A20)
123   FORMAT(/14X,'Costs :'/17X,'Initial :',T45,F5.2,' $/SQR.ft.'/
     $       17X,'Installation :',T45,F5.2,' $/SQR.ft.'/17X,
     $       'Annual maintenance :',T45,F5.2,' $/SQR.ft.'///
     $       14X,'Useful life :',T30,F5.2,' years.')
124   FORMAT(///14X,'Optical properties :'//T35,'Long wavelength')
125   FORMAT(T40,'Transmissivity :',T60,F5.2,' %.')
126   FORMAT(T40,'Emissivity :',T60,F5.2,' %.')
127   FORMAT(//T35,'Short wavelength')
128  FORMAT(T40,'Absorptivity :',T60,F5.2,' %.')
129   FORMAT(//11X,'Absorber : ',A20)
130   FORMAT(//11X,'Insulating material : ',A20)
131   FORMAT(///14X,'Thermal resistance :',F5.2,' HR-SQR.ft/Btu.')
132   FORMAT(5(/),11X,'AREAS'//14X,'Cover :',T30,F7.2,' SQR.ft.'/
     $       14X,'Absorber : ',T30,F7.2,' SQR.ft.'/14X,'Case : ',
     $       T30,F7.2,' SQR.ft.')
133   FORMAT(5(/),11X,'The air flow rate is ',F9.2,' CFM.'/11X,
     $       'The mass flow rate per'/11X,'unit area is  ',F7.2,
     $       ' lbs/SQR.ft.')
134   FORMAT(7(/),T19,'DAILY INFORMATION ON COLLECTOR PERFORMANCE')
135   FORMAT(/2x,'DAY   TOTAL     TOTAL     TOTAL    TOTAL   AVERAGE'
     $       '   AVERAGE  AVERAGE'/9X,'HOR.      DIR.      DIFF.     '
     $       'USEFUL  THERMAL    TEMP.    OUTLET'/9X,'RAD.      RAD'
     $       '      RAD.     HEAT     EFF.     INCREASE   TEMP.'//)
136   FORMAT(/14X,'Thickness of insulation : ',F4.1,' inches.')

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE SUBOUT2(DELTAT,ELCT,INTEREST,LPGAS,
     $       TOTQ,TOTLPE,AESAV)
C-----------------------------------------------------------------

      COMON/FANHEAT/FANINI,FANYRS,HEATINI,HEATYRS,TCEHEAT,
     $            TCFANCOLLE,TCFANGRAINE
      COMMON/TOTCOV/TINICOV,TINSCOV,TANUCOV
      COMMON/TOTABS/TINIABS,TINSABS,TANUABS
      COMMON/TOTINS/TINIINS,TINSINS,TANUINS
```

```
      COMMON/TCOST/ANCOLCOST,TANUALC,CORNBU
      COMMON/TENERGY/TEFAN,TFANGRAINE,TOTLPGAS,LPGSAV

      REAL*4 INTEREST
      REAL*4 HEATINI,HEATYRS
      REAL*4 LPGAS,LPGSAV


      WRITE(16,100)
      WRITE(16,101) TFANCOLLE
      WRITE(16,102) TFANGRAINE
      WRITE(16,103) DELTAT,TOTLPE,TOTLPGAS

      TOTQM = TOTQ/1.0E6
      CNESAV = AESAV - TCFANCOLLE

      WRITE(16,104) TOTQM,LPGSAV
      WRITE(16,105)
      WRITE(16,125)
      WRITE(16,126) ELCT
      WRITE(16,127) LPGAS
      WRITE(16,106)
      WRITE(16,107)
      WRITE(16,108) TINICOV,TINIABS,TINIINS
      WRITE(16,109) TINSCOV,TINSABS,TINSINS
      WRITE(16,110) TANUCOV,TANUABS,TANUINS
      WRITE(16,111) ANCOLCOST
      WRITE(16,112)
      WRITE(16,113) TCFANCOLLE
      WRITE(16,114) TCFANGRAINE
      WRITE(16,115) DELTAT,TCEHEAT
      WRITE(16,116) FANINI
      WRITE(16,117) FANYRS
      WRITE(16,118) HEATINI
      WRITE(16,117) HEATYRS
      WRITE(16,119) AESAV
      WRITE(16,128) CNESAV
      WRITE(16,120) INTEREST
      WRITE(16,121) CORNBU
      WRITE(16,122)

      IF(CNESAV.GT.ANCOLCOST) THEN
         WRITE(16,123)
      ELSE
         WRITE(16,124)
      ENDIF

100   FORMAT(///5X,'ENERGY CONSUMPTION : ')
101   FORMAT(//8X,'A. By Fan : - To drive the air through'
     $          ' the collector ',F7.2,' KW-HR')
102   FORMAT(19X,' - To drive the air through the grain ',F8.2,' KW-HR')
```

```
103   FORMAT(/8X,'B. By Heater : - To heat the air ',F3.0,' degrees F '
     $           ,'at night ',F7.2,' millions Btu.'/23X,'(Approximately
',
     $          F6.2,' gallons of LPG.)')
104   FORMAT(///5X,'TOTAL USEFUL HEAT COLLECTED BY SOLAR COLLECTOR '
     $          ,F7.2,' millions Btu.'/23X,'(Approximately ',F7.2
     $          ,' gallons of LPG.)')
105   FORMAT(////5X,'ECONOMIC ANALYSIS')
106   FORMAT(/8X,'COST OF COLLECTOR :')
107   FORMAT(/34X,'COVER',5X,'ABSORBER',4X,'INSULATION')
108   FORMAT(/10X,'Initial',15X,F8.2,3X,F8.2,5X,F8.2)
109   FORMAT(10X,'Installation',10X,F8.2,3X,F8.2,5X,F8.2)
110   FORMAT(10X,'Maintenance',11X,F8.2,3X,F8.2,5X,F8.2)
111   FRMAT(/10X,'EQUIVALENT ANNUAL COST OF SOLAR COLLECTOR $ ',F7.2)
112   FORMAT(///,7X,'Cost of the Energy Used : ')
113   FORMAT(/9X,'A. By Fan : - To drive the air through the collector'
     $          ,' $ ',F7.2)
114   FORMAT(21X,'- To drive the air through the grain $ ',F7.2)
115   FORMAT(/9X,'By Heater : - To heat the air ',F3.0,' degrees F '
     $          ,'at night $ ',F7.2)
116   FORMAT(//6X,'Initial Cost of the Fan $ ',F8.2)
117   FORMAT(6X,'Useful life ',F3.0,' years')
118   FORMAT(/6X,'Initial Cost of the Heater $ ',F8.2)
119   FORMAT(//4X,'ANNUAL ENERGY SAVINGS DUE TO SOLAR'
     $       ,' COLLECTOR $ ',F7.2)
120   FORMAT(///,4X,'Assuming that the same amount of corn will'
     $    /4X,' be dried each year during the useful life of the '
     $    'system'/4X,'and an interest on the money of ',F3.0,' %.')
121   FORMAT(//9X,'COST OF DRYING CORN ',F5.2,' $/Bu')
122   FORMAT(//,4X,'Based on the assumptions stated above, the equi'
     $          ,'valent annual'/5X,'cost of the solar collector '
     $          ,'and the net annual energy savings,')
123   FORMAT(5X,'IT IS RECOMMENDED TO INSTALL THE SOLAR COLLECTOR.')
124   FORMAT(5X,'IT IS NOT RECOMMENDED TO INSTALL THE SOLAR COLLECTOR.')
125   FORMAT(5X,'PRICES OF ENERGY :')
126   FORMAT(//10X,'ELECTRICITY',T22,F5.2,' $/KW-HR')
127   FORMAT(10X,'L.P. GAS',T22,F5.2,' $/gal')
128   FORMAT(4X,'NET ANNUAL ENERGY SAVINGS DUE TO SOLAR COLLECTOR '
     $       ,'$',F7.2)

      RETURN
      END


C-----------------------------------------------------------------------
      SUBROUTINE SUSPENDED(SHAPE)
C-----------------------------------------------------------------------

      COMMON/AIRVARIABLES/AIRMASS,AIRVEL,CFM
      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/AIRPROPERTIES/CP,K,MU,ROAIR
```

```
      COMMON/DIMENSIONS/NO,L1,L2,L3
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2


      REAL*4 L1,L2,L3
      REAL*4 K,MU

      IF(SHAPE.EQ.3.0) THEN

200      WRITE(1,100)
         READ(1,20,ERR=150) X2

         IF(X2.LT.0.0.OR.X2.GT.L3) THEN

150         WRITE(1,101)
            GO TO 200

         ENDIF

         A2 = X2*L2
         DH2 = 2*A2 / (X2+L2)
         RE2 = ROAIR*AIRVEL*DH2*60. / MU

         A1 = ACROSS - A2
         DH1 = 2.*A1 / ((L3 - X2) + L2)
         RE1 = ROAIR*AIRVEL*DH1*60. / MU

      ELSE

300      WRITE(1,102)
         READ(1,20,ERR=250) X2

         IF(X2.LT.0.OR.X2.GT.L3) THEN

250         WRITE(1,101)
            GO TO 300

         ENDIF

         A2 = X2*L2 / 2.
         P2 = 2. * SQRT(X2**2 + (L2/2.)**2) + L2
         DH2 = 4.*A2 / P2
         RE2 = ROAIR*AIRVEL*DH2*60. / MU

         A1 = ACROSS - A2
         P1 = 2. * P2 + PER - L2
         DH1 = 4.*A1 / P1
         RE1 = ROAIR*AIRVEL*DH1*60. / MU
```

```
      ENDIF

      G1 = AIRMASS * 60. * A1 / ACROSS
      G2 = AIRMASS * 60. * A2 / ACROSS

20    FORMAT(F5.0)
100   FORMAT(10(/),5X,'WHAT IS THE HEIGTH OF THE ABSORBER FROM',
     $          ' THE BOTTOM ? (ft)',5(/))
101   FORMAT(10(/),5X,'PLEASE CHECK YOUR ANSWER AND INPUT IT AGAIN.')
102   FORMAT(10(/),5X,'WHAT IS THE MAXIMUM HEIGTH OF THE ABSORBER',
     $          ' FROM THE BOTTOM ? (ft)',5(/))

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE TEMPF(TYPE)
C-----------------------------------------------------------------

      COMON/AIRPROPERTIES/CP,K,MU,ROAIR
      COMMON/AREAS/AABS,ABOT,ABSNO,ACOV,ACROSS,PER,RACOV,RABOT
      COMMON/COLLECTOR/A1,A2,DEN,DEN1,DEN2,DH,DH1,DH2,
     $       GCROSS,G1,G2,H1,H2,H2P,H2PP,H3,RE,RE1,RE2,
     $       TIN,TIN1,TIN2
      COMMON/TEMPERATURES/T1,T2,T3,TF,TF1,TF2

     REAL*4 H1,H2,H2P,H2PP,H3

      IF(TYPE.EQ.1.0) THEN

         COEF = 2.*GCROSS*CP / ABSNO
         TF = (COEF*TIN + RACOV*H1*T1 + H2*T2) /
     $        (COEF + RACOV*H1 + H2)

      ELSEIF(TYPE.EQ.2.0) THEN

         COEF1 = 2.0*G1*CP / ABSNO
         COEF2 = 2.0*G2*CP /ABSNO
         TF1 = (COEF1*TIN1 + H2P*T2 + RACOV*H1*T1) /
     $         (COEF1 + RACOV*H1 + H2P)
         TF2 = (COEF2*TIN2 + H2PP*T2 + RABOT*H3*T3) /
     $         (COEF2 + H2PP + RABOT*H3)

      ELSE

         COEF = (2. * GCROSS * CP) / ABSNO
         TF = (COEF*TIN + H1*T1 + RABOT*H2*T2) /
     $         (COEF + H1 + RABOT*H2)

      ENDIF
```

```
      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE TEMPGENERATOR(TAMB,TYPE)
C-----------------------------------------------------------------

      COMMON/TEMPERATURES/T1,T2,T3,TF,TF1,TF2

      IF(TYPE.EQ.1) THEN
         T1 = TAMB
         T2 = TAMB + 20.
      ELSEIF(TYPE.EQ.2) THEN
         T1 = TAMB + 5.
         T2 = TAMB + 40.
         T3 = TAMB + 30.
      ELSE
         T1 = TAMB + 50.
         T2 = TAMB + 20.
      ENDIF

      RETURN
      END


C-----------------------------------------------------------------
      SUBROUTINE TIMED1(DAYS1,FACTOR)
C-----------------------------------------------------------------

      REAL*4 MD

10    FORMAT(A1)
11    FORMAT(A72)
12    FORMAT(///(A72))
13    FORMAT(/A72)

      CHARACTER*1 ALPHA3
      CHARACTER*72 ALPHA(11),TEXT1(5)

      OPEN(9,FILE='TEXT1')
      READ(9,11) (ALPHA(I),I=1,11),(TEXT1(I),I=1,5)
      CLOSE(9)

      WRITE(1,12) (TEXT1(I),I=1,5)
990   WRITE(1,13) ALPHA(1)
      READ(1,10) ALPHA3

      IF(ALPHA3.EQ.'Y') THEN
```

```
1000     WRITE(1,11) ALPHA(2)
         READ(1,*) MD

         IF(MD.LT.2.0.OR.MD.GT.50.) THEN

            WRITE(1,13) (ALPHA(I),I=3,4)
            GO TO 1000

         ELSE

            FACTOR = (1.3266 - 0.04555*MD)

         ENDIF

      ELSEIF(ALPHA3.EQ.'N') THEN

            FACTOR = 1.0
      ELSE

            WRITE(1,13) ALPHA(7)
            GO TO 990

      ENDIF

1010  WRITE(1,13) (ALPHA(I),I=5,6)
      READ(1,10) ALPHA3

      IF(ALPHA3.NE.'Y'.AND.ALPHA3.NE.'N') THEN

         WRITE(1,13) ALPHA(7)
         GO TO 1010

      ENDIF

      IF(ALPHA3.EQ.'N') THEN

         DAYS1 = 0.

      ELSE

         WRITE(1,13) ALPHA(8)
         READ(1,*) DAYS1

      ENDIF

      RETURN
      END
```

```
C-----------------------------------------------------------------------
      FUNCTION TRANS(REF,ANGLE)
C-----------------------------------------------------------------------

C          FUNCTIONS TO DETERMINE TRANSMISSIVITY
C          OF THE COVER AS A FUNCTION OF THE ANGLE.
C          DATA TAKEN FROM ASAE PAPER No.77-4013
C          SOLAR AND LONG WAVELENGTH TRANSMISSION
C          OF MATERIALS, BY GODBEY ET AL. SEE COM
C          PLETE REFERENCE ON THE THESIS.

      CHARACTER*6 REF

      IF(REF.EQ.'POLYET') THEN

         A = 91.87642
         B = 0.596821
         C = (-6.773251E-02)
         D = 1.904472E-03
         E = (-1.653285E-05)

      ELSEIF(REF.EQ.'RFGLAS') THEN

         A = 86.89533
         B = 0.1741256
         C = (-4.129718E-02)
         D = 1.359614E-03
         E = (-1.313645E-05)

      ELSEIF (REF.EQ.'PFGLAS') THEN

         A = 76.99157
         B = 0.1462668
         C = (-0.003292247)
         D = (-1.295998E-04)
         E = 0.

      ELSEIF(REF.EQ.'CFGLS1') THEN

         A = 83.48315
         B = (-0.4705833)
         C = 3.011893E-02
         D = (-4.765853E-04)
         E = 0.

      ELSEIF(REF.EQ.'GLASS') THEN

         A = 89.25328
         B = (-0.1365373)
         C = 6.896083E-03
```

```
         D = (-1.197128E-04)
         E = 0.

      ELSE

         WRITE(1,*) ' ERROR READING TRANSMISSIVITY FUNCTION.'

      ENDIF

      Y = A + ANGLE*(B + ANGLE*(C + ANGLE*(D + ANGLE*E)))

C     .....CORRECTING OUT OF RANGE VALUES.....

      IF(Y.LT.0.) Y = 0.
      IF(Y.GT.100.) Y = 100.


      TRANS = Y/100.

      RETURN
      END


C-----------------------------------------------------------------
      FUNCTION WBDBDP(DB,DP)
C-----------------------------------------------------------------

      EXTERNAL WBDBP1

      DB1=DB+3.0

      IF(DB1.GT.211.99) DB1=211.99

      DP1=DP-1.
      CALL SEARCH(WBDBP1,DB1,DP1,0.01,WB,DB,DP)
      WBDBDP=WB

      RETURN
      END


C-----------------------------------------------------------------
      FUNCTION WBDBP1(WB,DB,DP)
C-----------------------------------------------------------------

      PV=PSDB(DP)
      WBDBP1=WB-DB-(PSDB(WB)-PV)/BPVWB(PV,WB)

      RETURN
      END
```

```
C-----------------------------------------------------------------------
      REAL*4 FUNCTION WBTODB(X)
C-----------------------------------------------------------------------

C     THIS FUNCTION DETERMINES MOISTURE CONTENT DRY BASIS FROM
C     MOISTURE CONTENT WET BASIS.  INPUT SHOULD BE DECIMAL
C     AND OUTPUT IS DECIMAL.

      WBTODB = X/(1-X)

      RETURN
      END
```

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BIOGRAPHICAL SKETCH

Jose Antonio Torres, born in Bogotá, Colombia, December 5, 1958. He studied at the Universidad del Valle, Cali, Colombia, from 1977 to 1980. In 1981 he continued his undergraduate studies at the University of Florida, Gainesville, FL, and finished those on May 1984. The fall of that same year he started his Master in Engineering degree.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Engineering.

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Erich A. Farber
Professor of Mechanical Engineering

This thesis was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Master of Engineering.

August, 1987

Dean, College of Engineering

Dean, Graduate School